The search for leptonic CP violation

Enrique Fernández Martínez

νProbes

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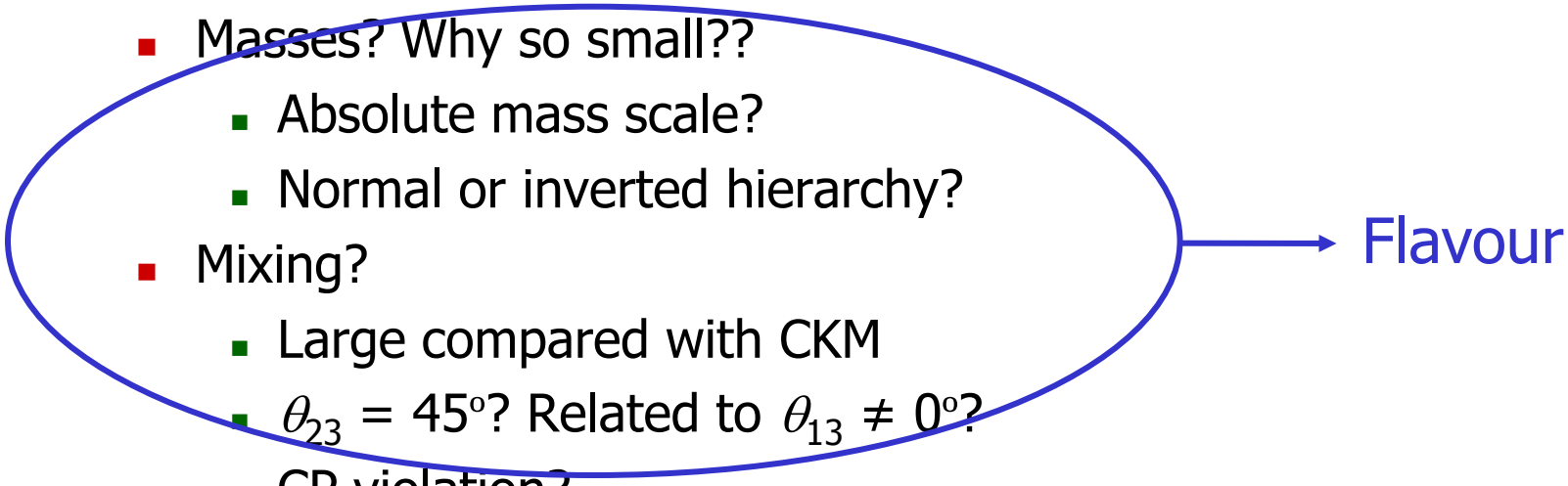

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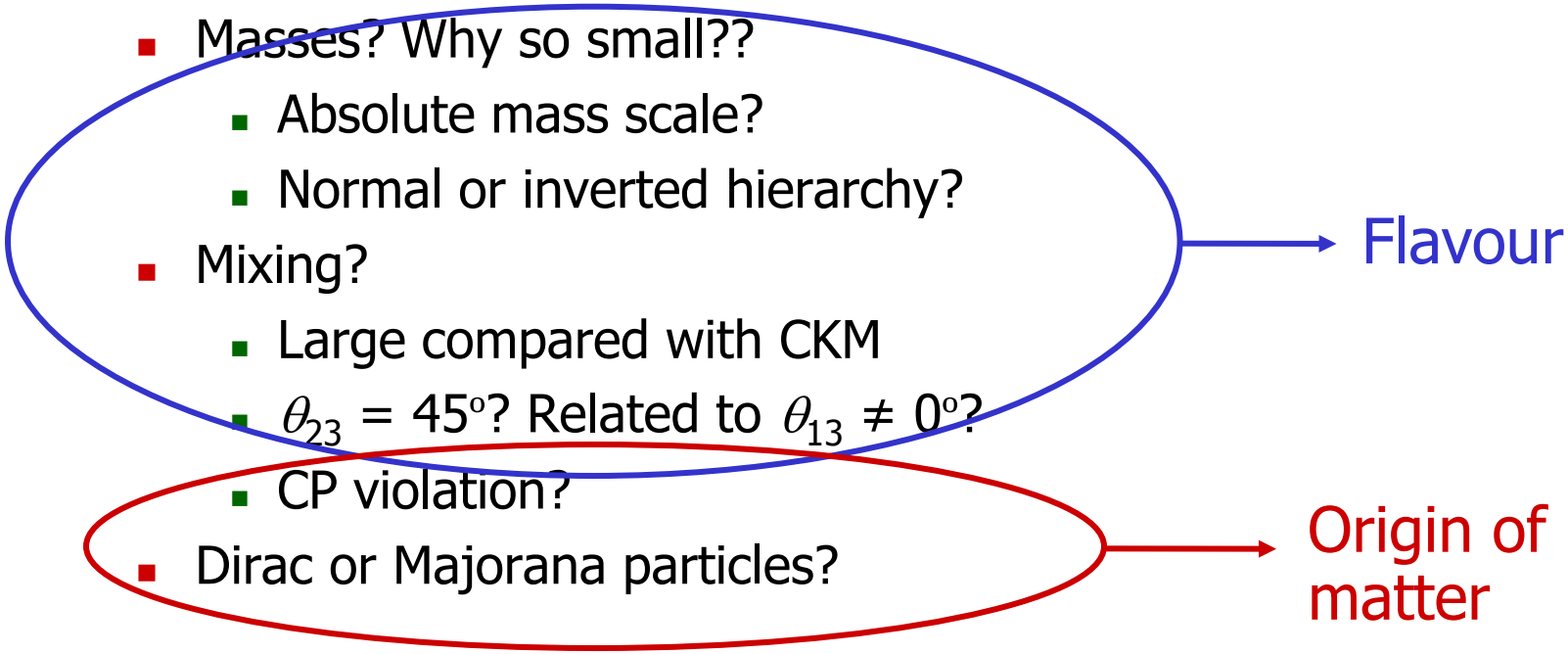

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Flavour

Origin of matter

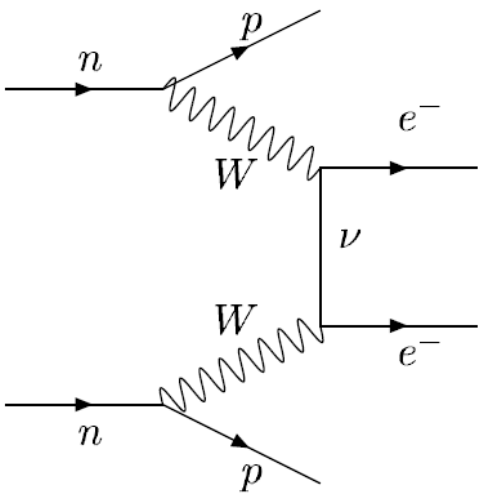
- New generation of neutrino experiments to address these questions is now running!

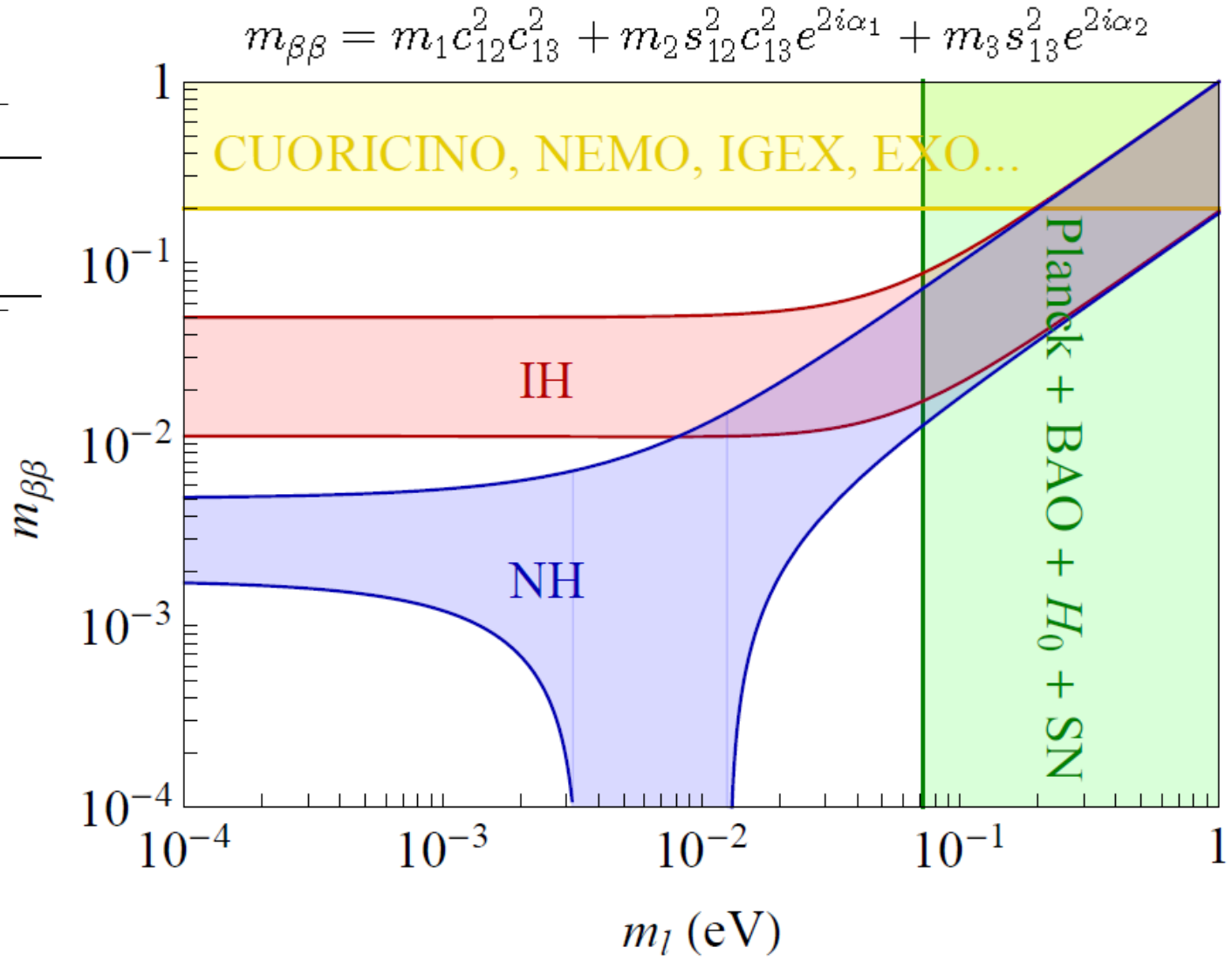
Oscillation Parameters

- What we already know (1σ)
  - Solar sector $\begin{cases} \Delta m^2_{21} = 7.45^{+0.19}_{-0.16} \cdot 10^{-5}\,\mathrm{eV}^2 \\ \sin^2\theta_{12} = 0.306^{+0.012}_{-0.012} \end{cases}$
  - Atm. sector $\begin{cases} \Delta m^2_{31} = 2.417^{+0.013}_{-0.013} \cdot 10^{-3} \,/\, -2.410^{+0.062}_{-0.062} \cdot 10^{-3}\ \mathrm{eV}^2 \\ \sin^2\theta_{23} = 0.446^{+0.007}_{-0.007} \,/\, 0.587^{+0.032}_{-0.037} \end{cases}$
  - $\sin^2\theta_{13} = 0.0229^{+0.002}_{-0.0019}$
- What we still don't know
  - $\delta = ?$
  - Mass hierarchy $s_{atm} = sign\left(\Delta m^2_{31}\right)$

M. C. Gonzalez-Garcia, M. Maltoni, J. Salvado, T. Schwetz 1209.3023 www.nu-fit.org
See also: D. V. Forero, M. Tortola, J. Valle 1205.4018
G.L. Fogli, E. Lisi, A. Marrone, D. Montanino, A. Palazzo, A.M. Rotunno 1205.5254

Plus non-oscillation searches:





Plot updated from M. Blennow, EFM, J. Lopez-Pavon and J. Menendez 1005.3240

The Golden channel in matter

$$P\left(\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_\mu\right) = s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{atm}}{\tilde{B}_{\mp}}\right)^2 \sin^2\left(\frac{\tilde{B}_{\mp} L}{2}\right)$$ "atmospheric"

$$+ c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{sol}}{A}\right)^2 \sin^2\left(\frac{AL}{2}\right)$$ "solar"

"interference" $+ \tilde{J} \frac{\Delta_{sol}}{A} \frac{\Delta_{atm}}{\tilde{B}_{\mp}} \sin\left(\frac{AL}{2}\right) \sin\left(\frac{\tilde{B}_{\mp} L}{2}\right) \cos\left(\pm\delta - \frac{\Delta_{atm} L}{2}\right)$

Expanded in

$\sin 2\theta_{13} \sim 0.3$ $\qquad \left(\frac{\Delta_{sol} L}{2}\right) \cong 0.05$

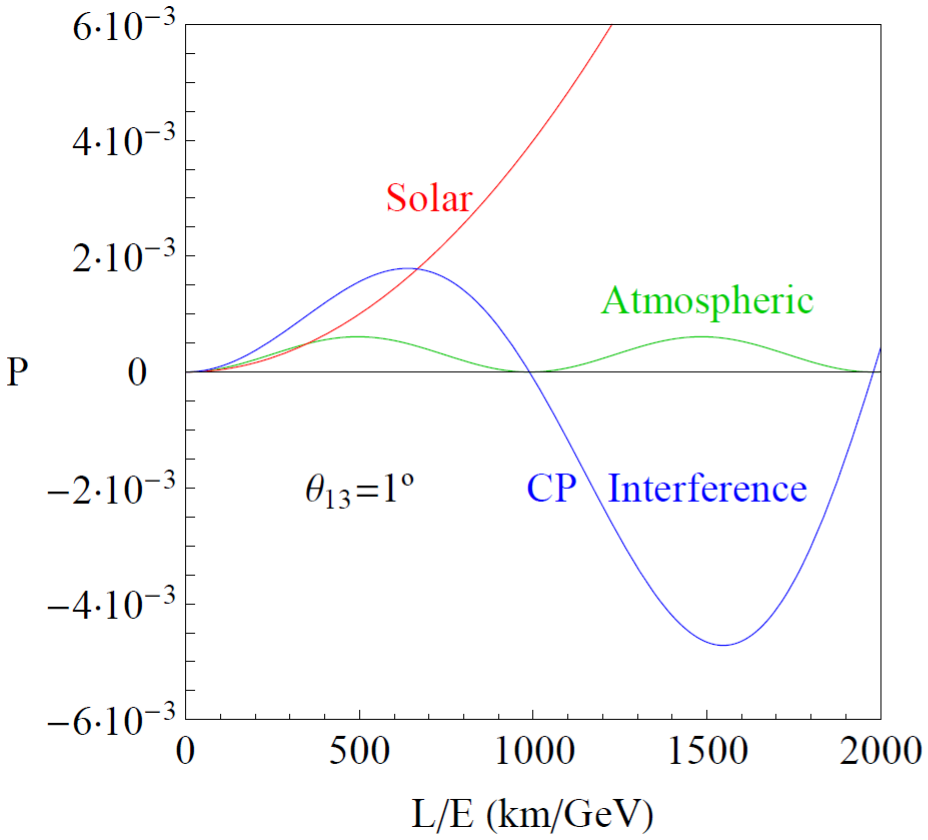
where

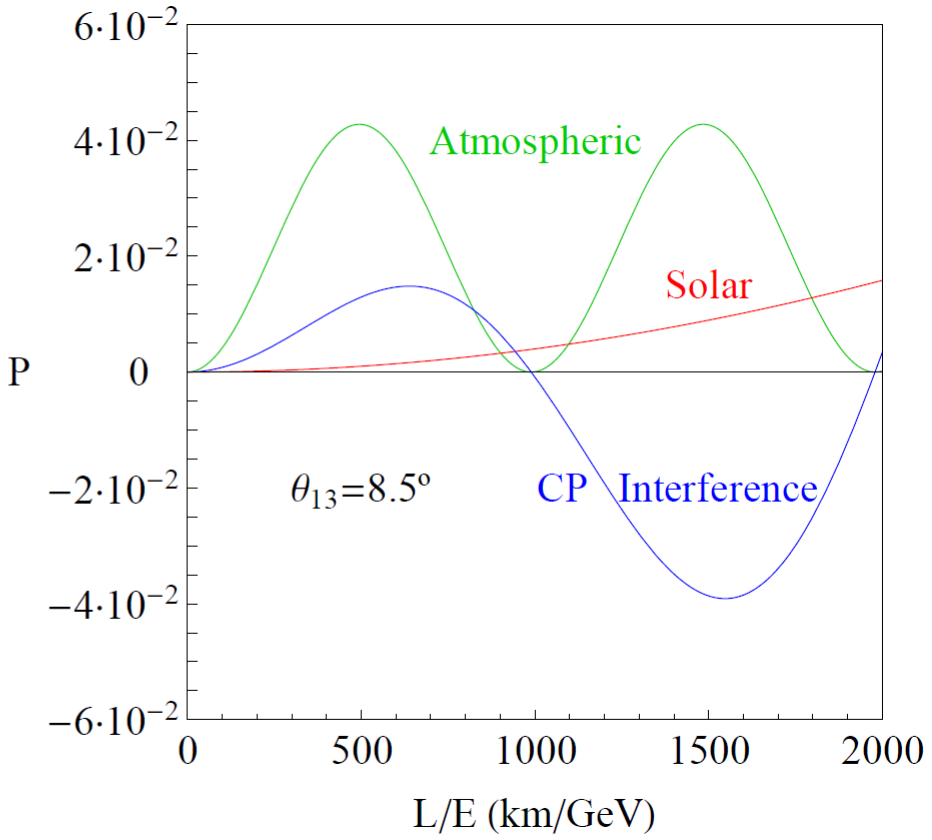
$\tilde{J} = \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23}$ $\qquad \Delta_{atm} = \frac{\Delta m_{23}^2}{2E}$ $\qquad \Delta_{sol} = \frac{\Delta m_{12}^2}{2E}$

$A = \sqrt{2} G_F n_e$ $\qquad \tilde{B}_{\mp} = \left|A \mp \Delta_{atm}\right|$

A. Cervera *et al.* hep-ph/0002108

Optimization of facilities for large θ_{13}





Signal systematics and not stats becomes the bottleneck for large θ_{13}, explore second peak? P. Coloma and EFM 1110.4583

Shoplist of present and future facilities

Experiment	Detector (kton)	Baseline (km)	Power (MW)	Mean ν E (GeV)
T2K	22 WC	275	0.2-0.7	~1
NOνA	13 scintillator	810	0.75	~2.5
T2HK	560 WC	275	0.7	~1
LBNF (DUNE)	30 LAr	1300	1.2	~3
ESS	500 WC	540	5	~0.4

T2K and NOνA currently running

T2HK and LBNF will hopefully be aproved soon

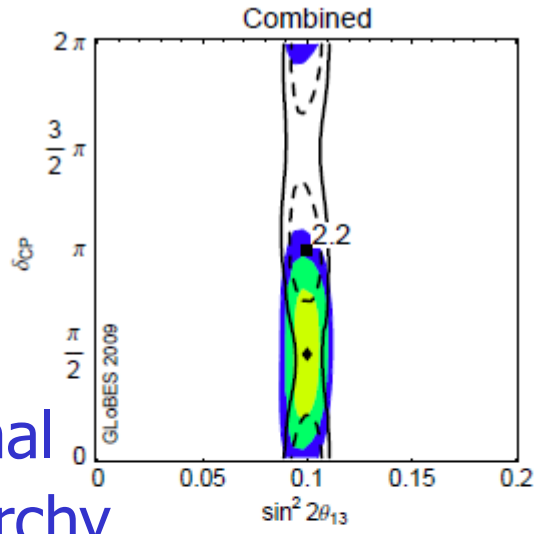
T2K, T2HK and ESS low E and short baseline → small matter effects, large WC det. Good for CP violation.

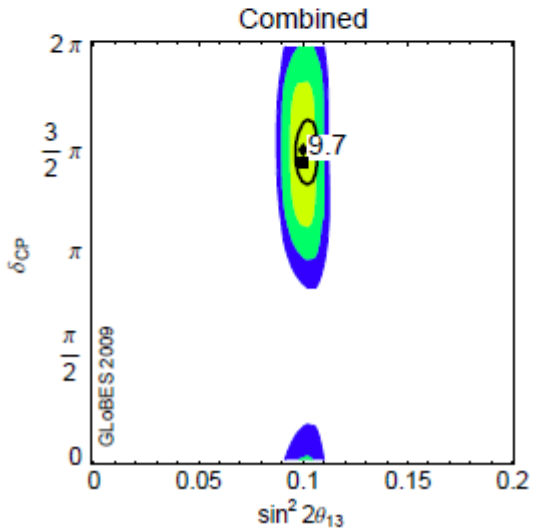
NOνA and LBNF high E and long baseline → large matter effects, smaller det. Good for mass hierarchy.

Sensitivities with present experiments

1, 2 and 3 σ

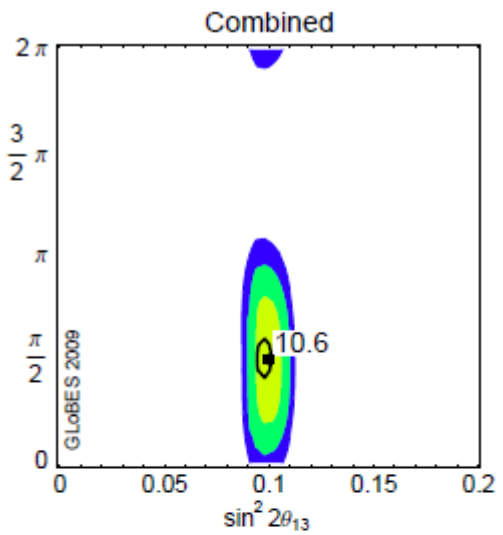
Normal hierarchy

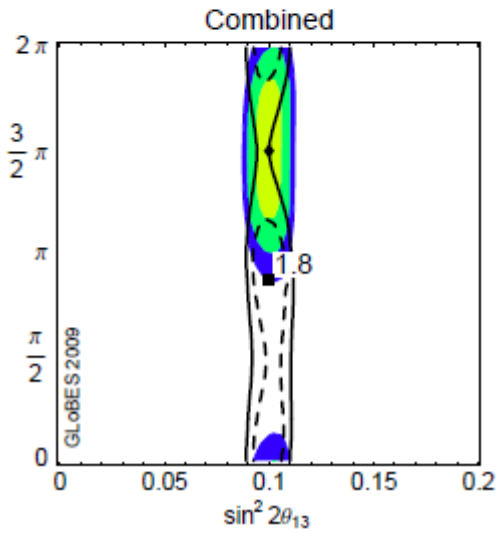




T2K+
Nova+
Daya Bay

Inverted hierarchy





From P. Huber *et al.* 0907.1896

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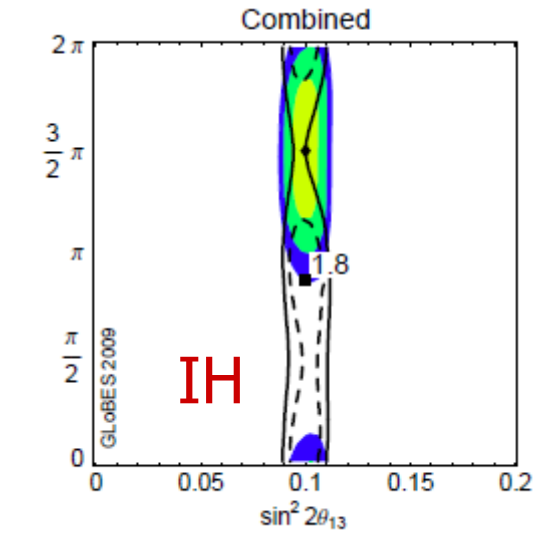
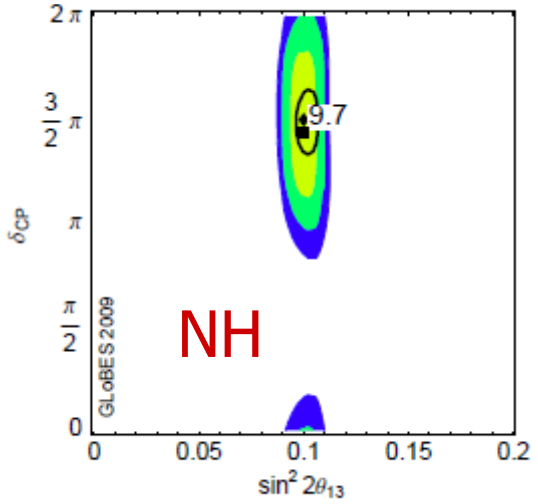
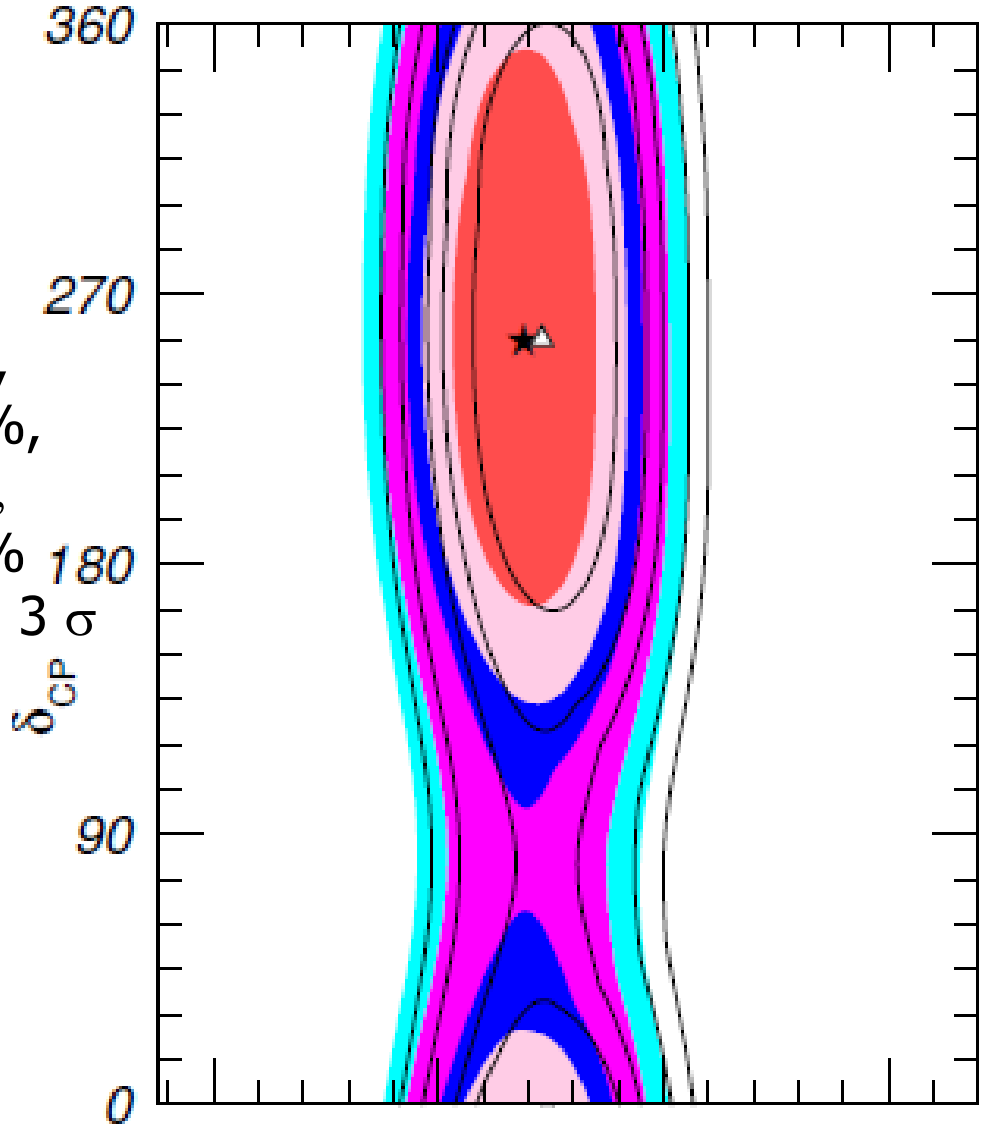


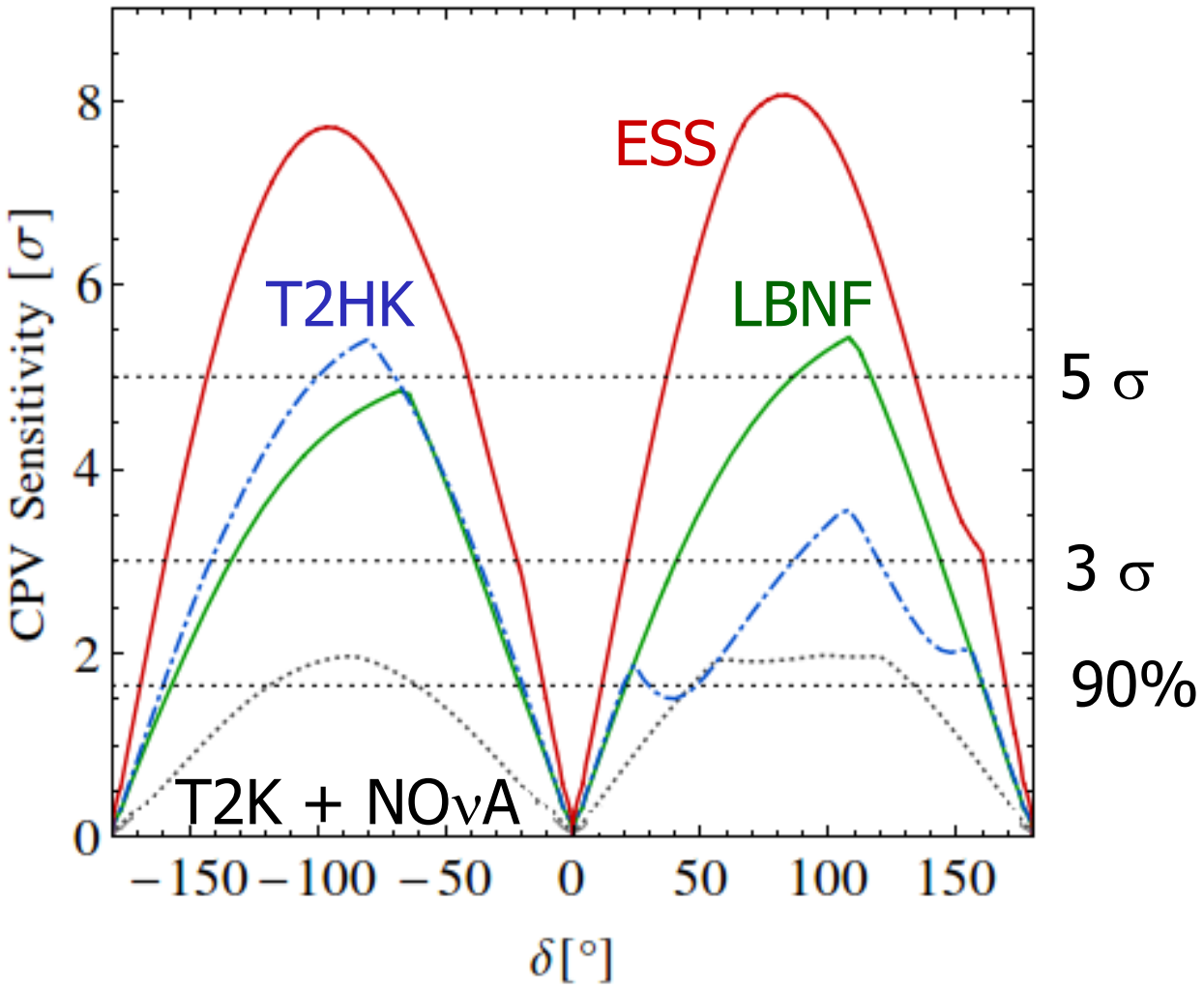


1 σ,
90%,
2 σ,
99%
and 3 σ



From M. C. Gonzalez-Garcia, M. Maltoni, J. Salvado, T. Schwetz 1405.5439 www.nu-fit.org

Sensitivities to CPV



Plot adapted by P. Coloma from E. Baussan *et al.* 1309.7022

Is it a χ^2?

To plot these: compute $\Delta\chi^2=\chi^2(\delta=0,\pi)-\chi^2_{min}$ for a given "true" δ

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Why 1, 4, 9, 25?

Wilk's theorem says $\Delta\chi^2$ should be distributed as χ^2 a with 1 dof

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Wilk's theorem asumes linearity of the observables to have a χ^2

M. Blennow, P. Coloma and EFM 1407.3274

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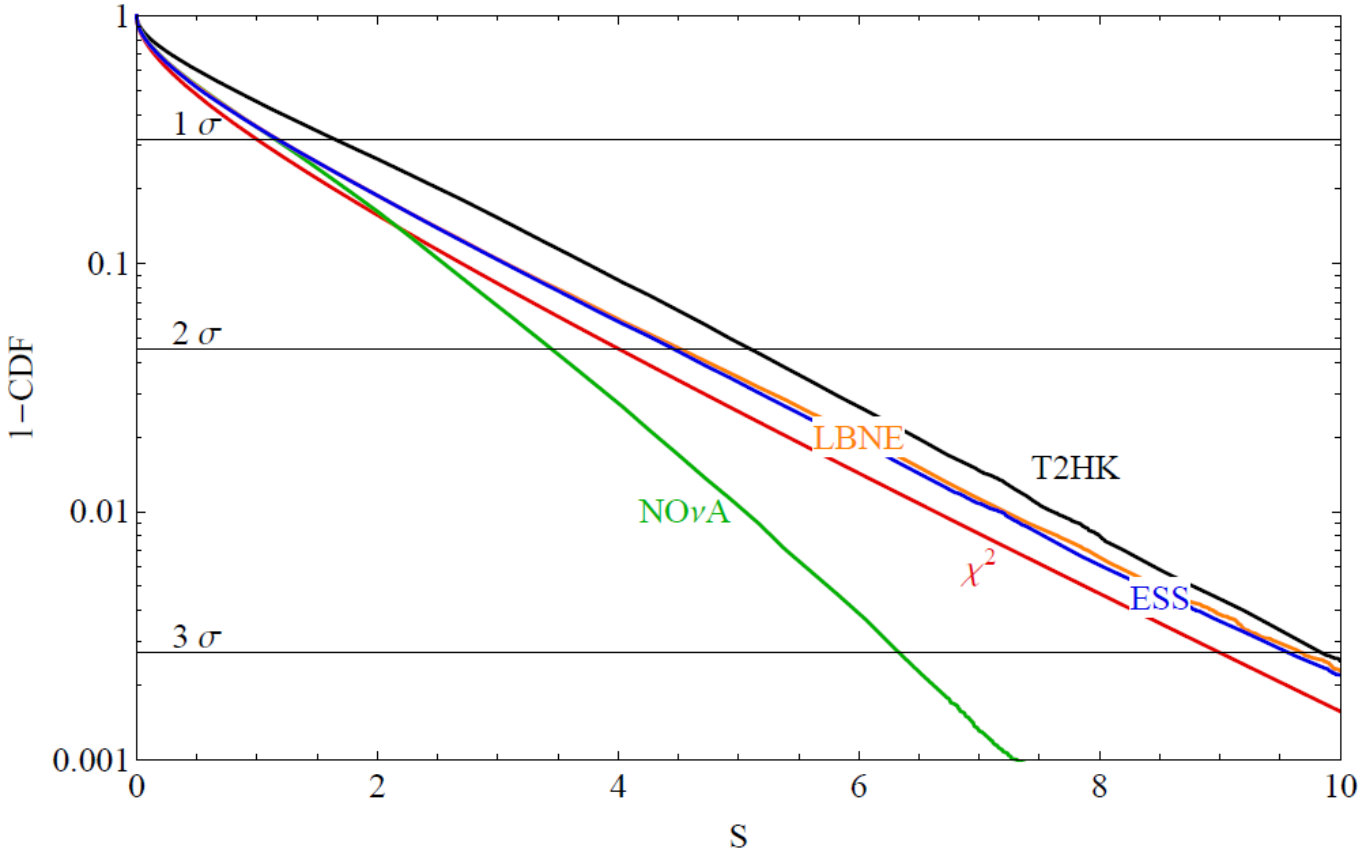

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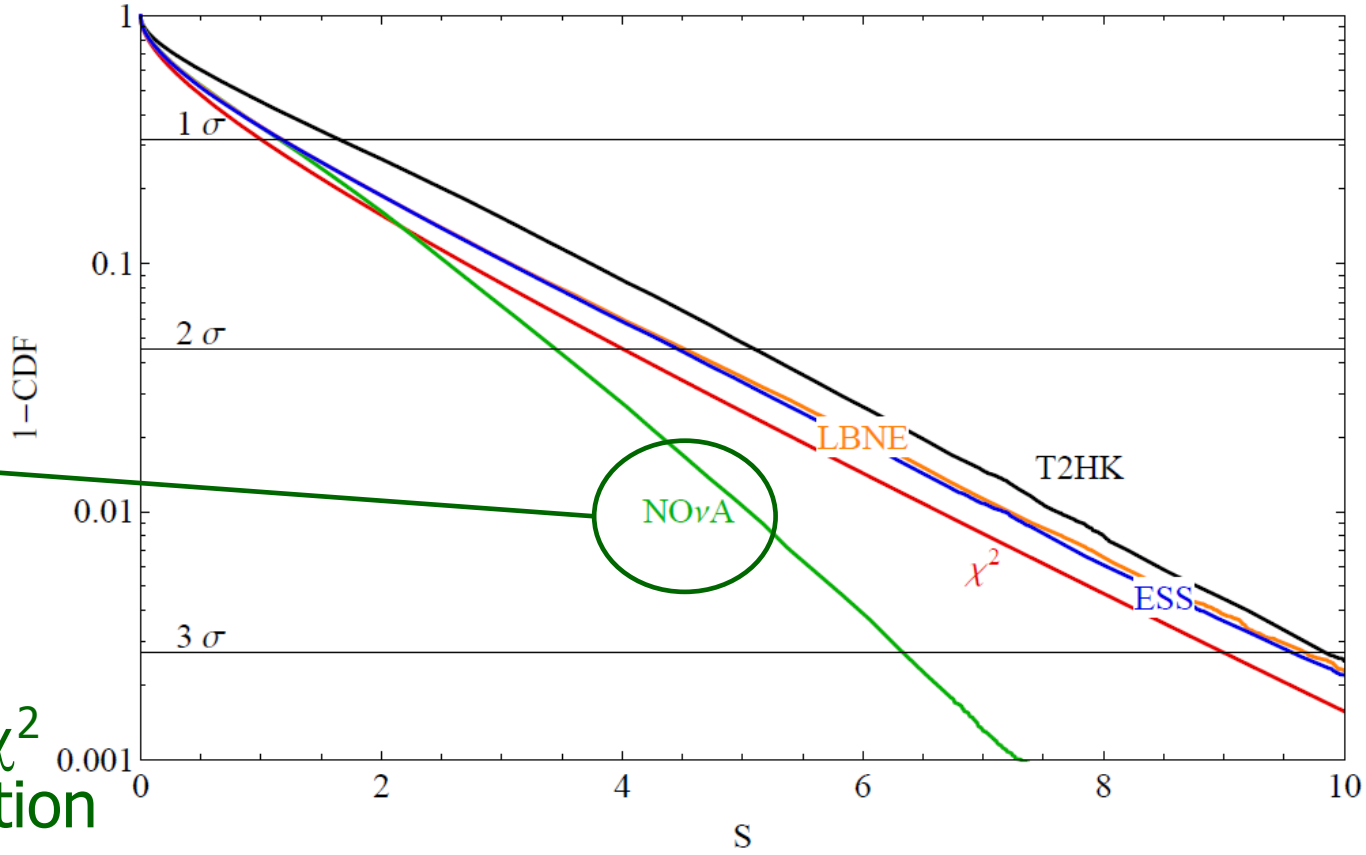

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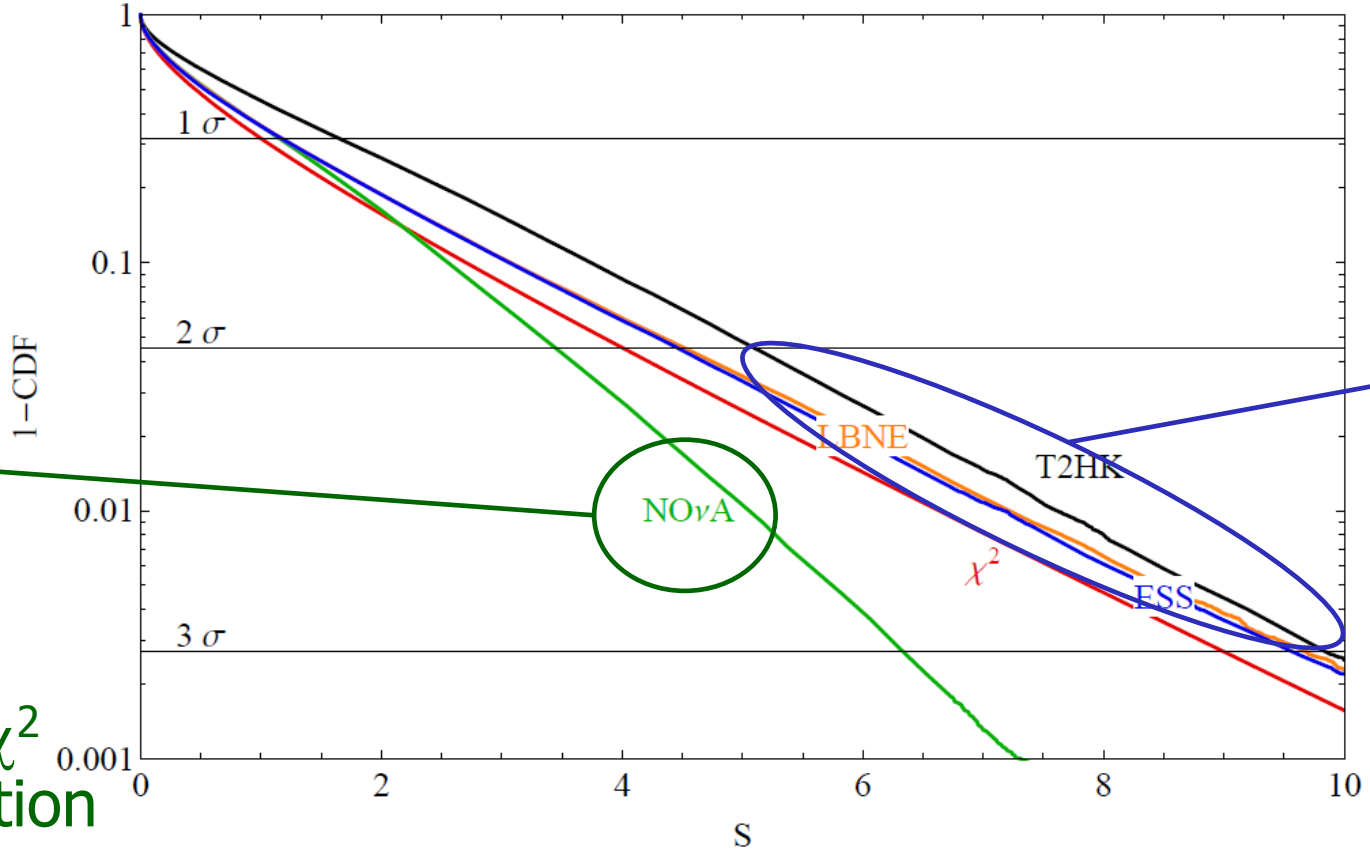

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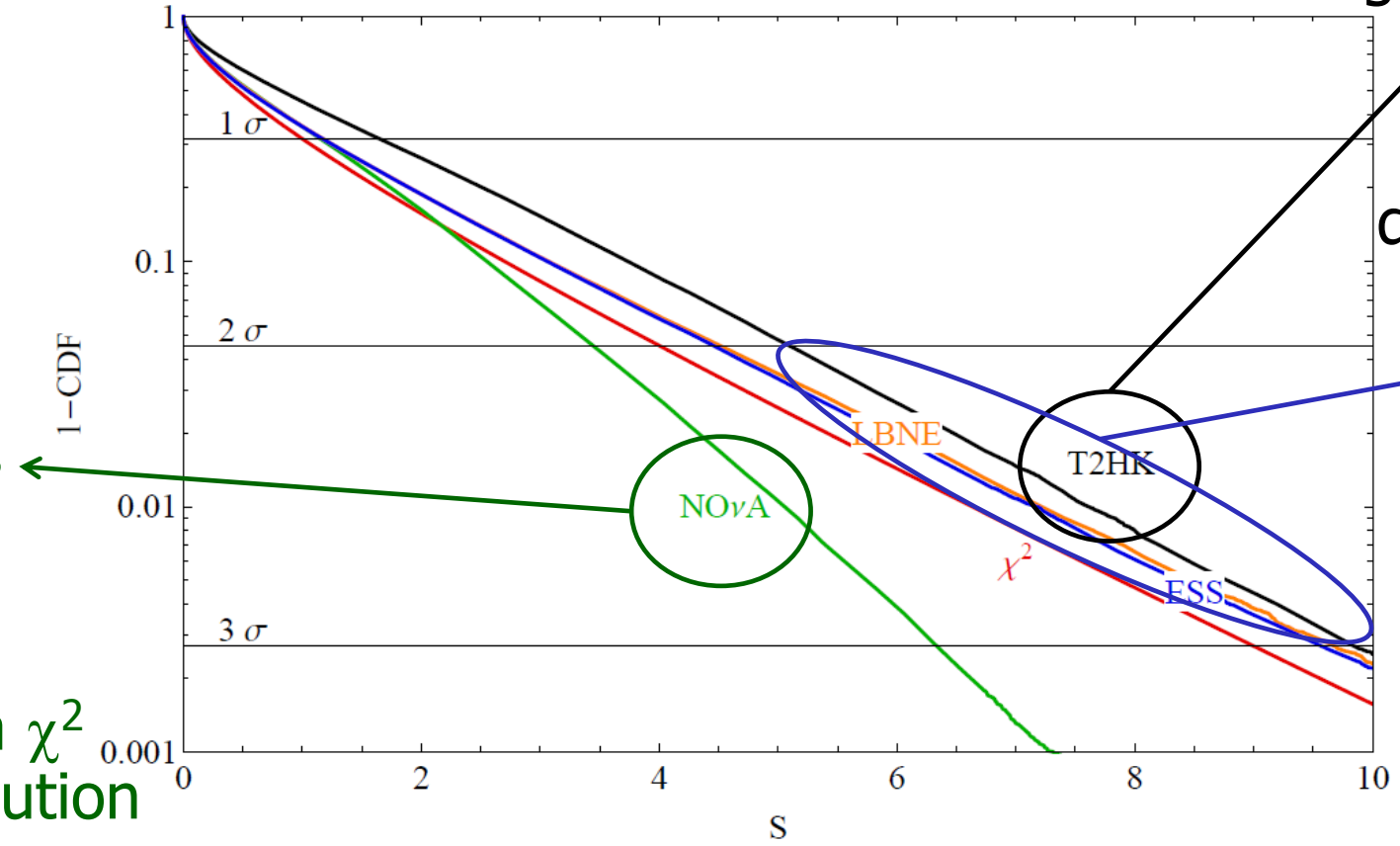
T2HK degeneracies induce further deviations



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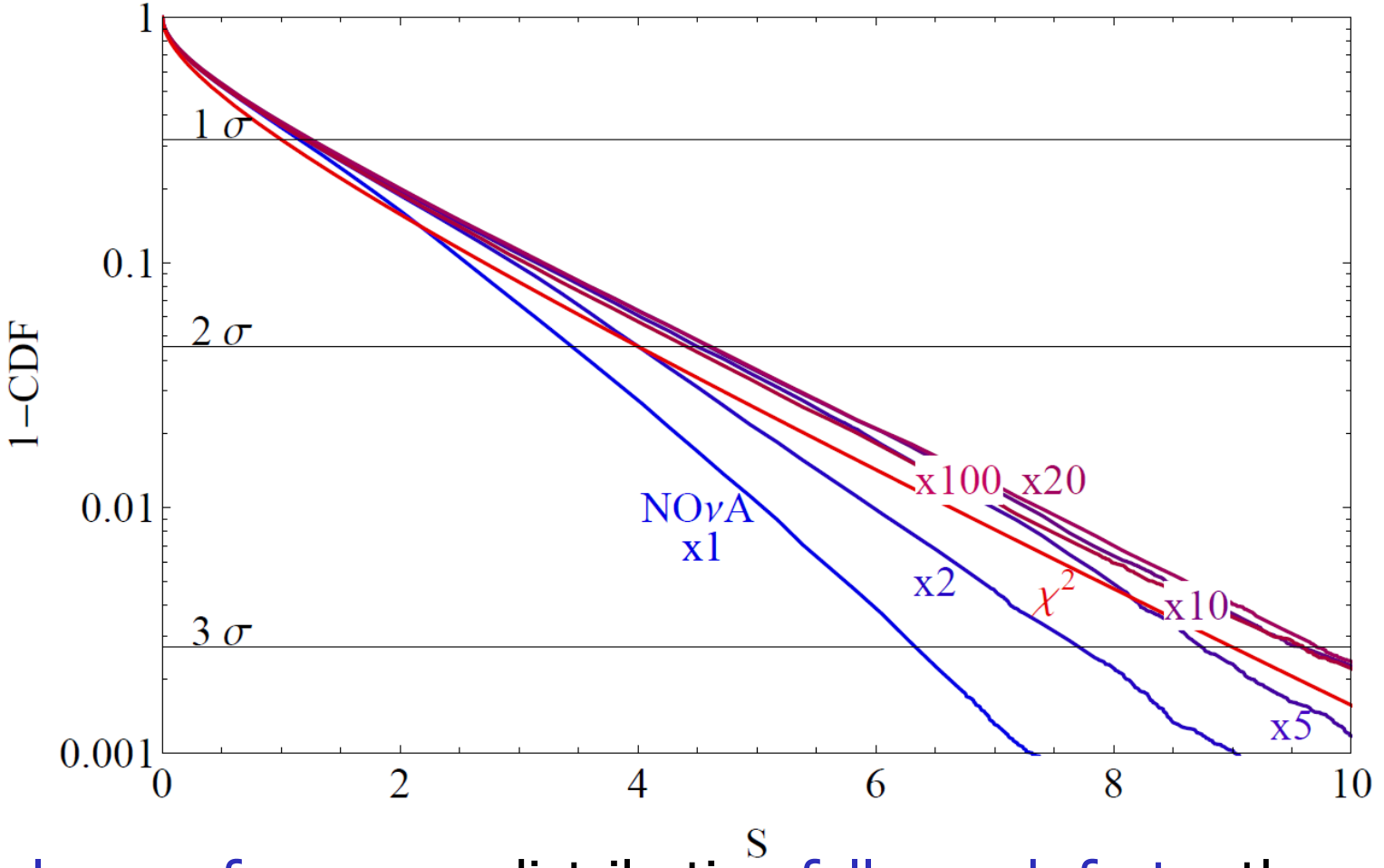

For low performance, distribution falls much faster than χ^2

As the performance improves, first it falls slower and then aproaches asymprocically a χ^2 M. Blennow, P. Coloma and EFM 1407.3274

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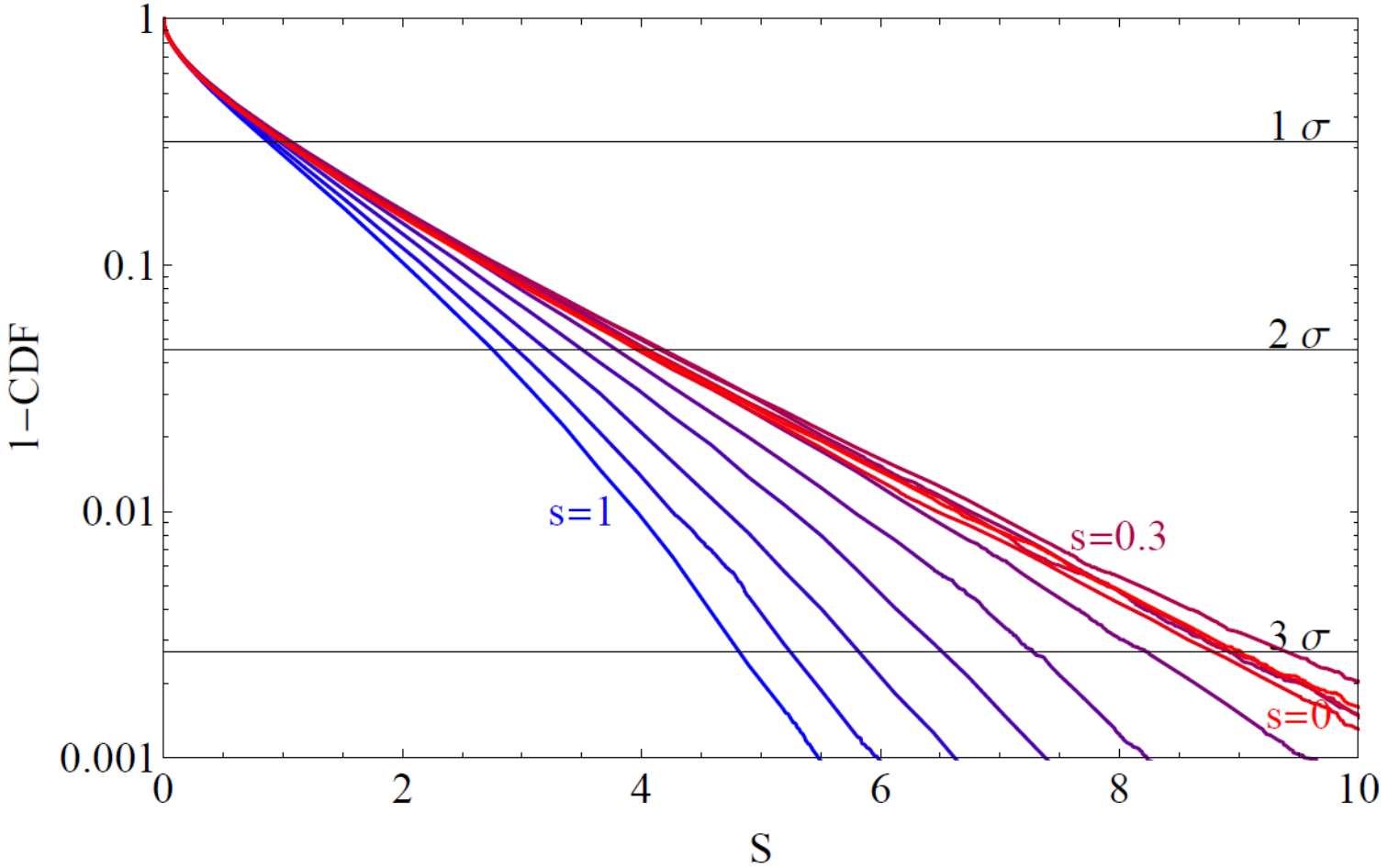

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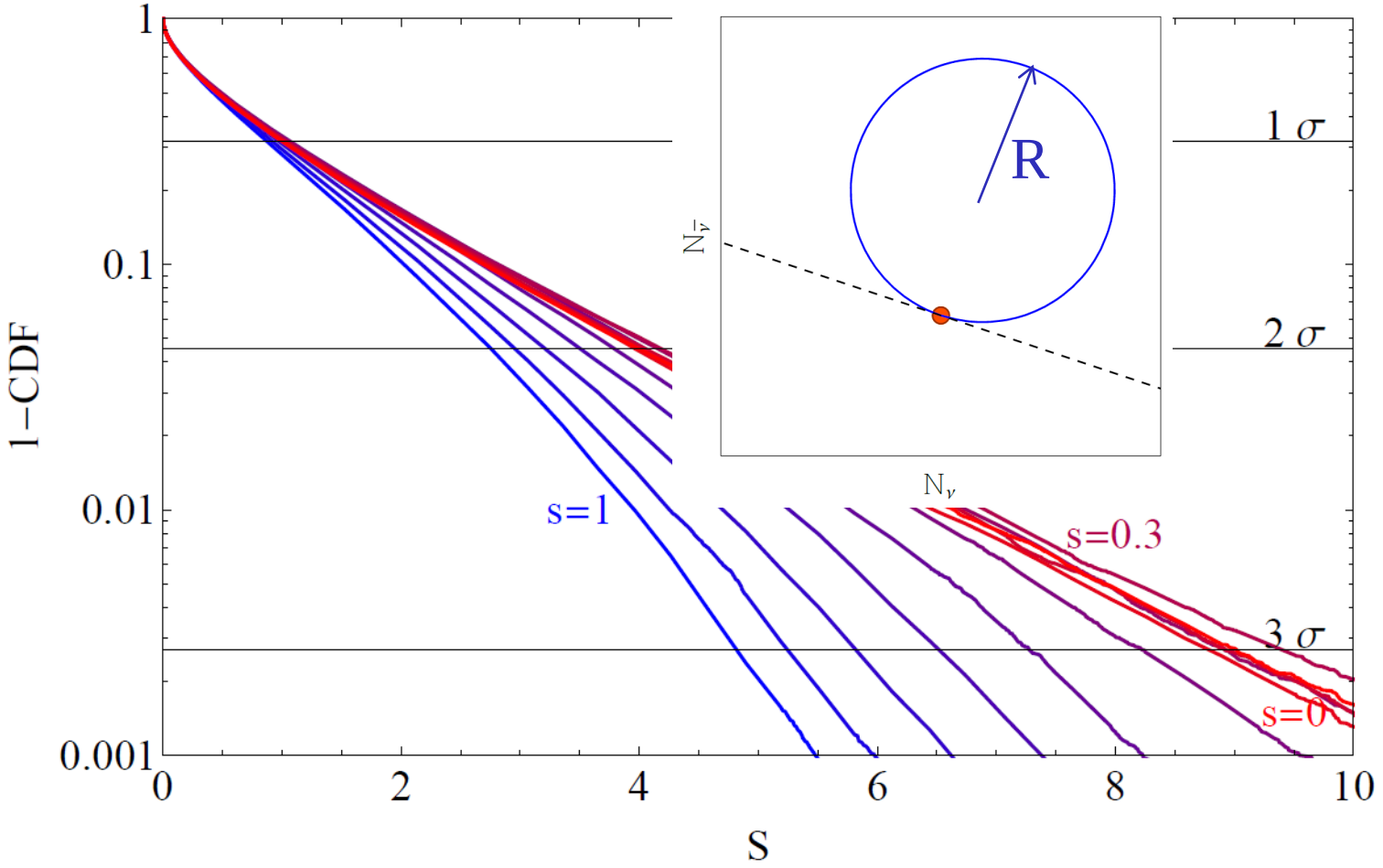

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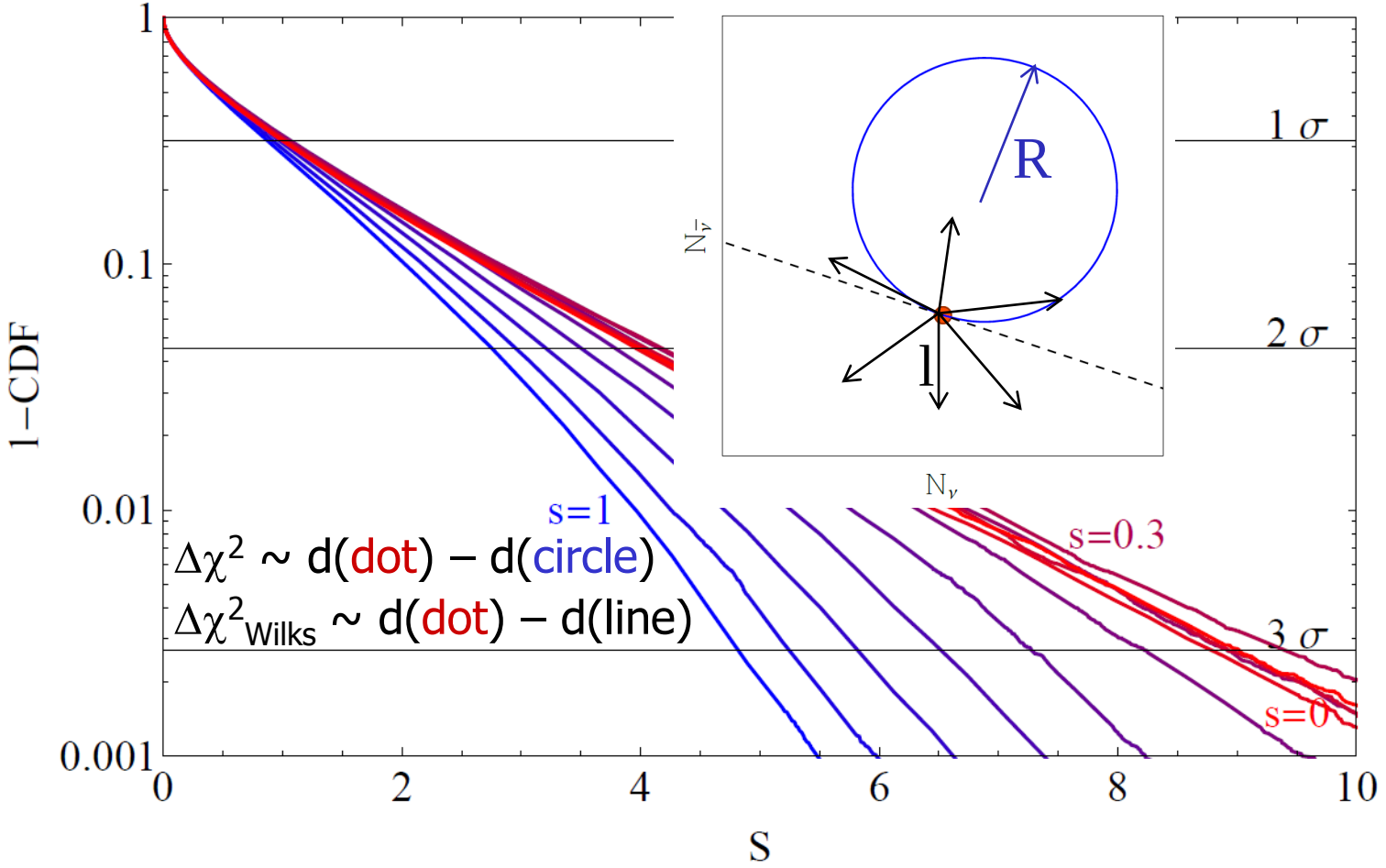

Statistical fluctuations around the test point (δ=0) will have a characteristic size $l = s\,R$. For large s distance to circle is larger than line → smaller difference with distance to point → smaller test stat.

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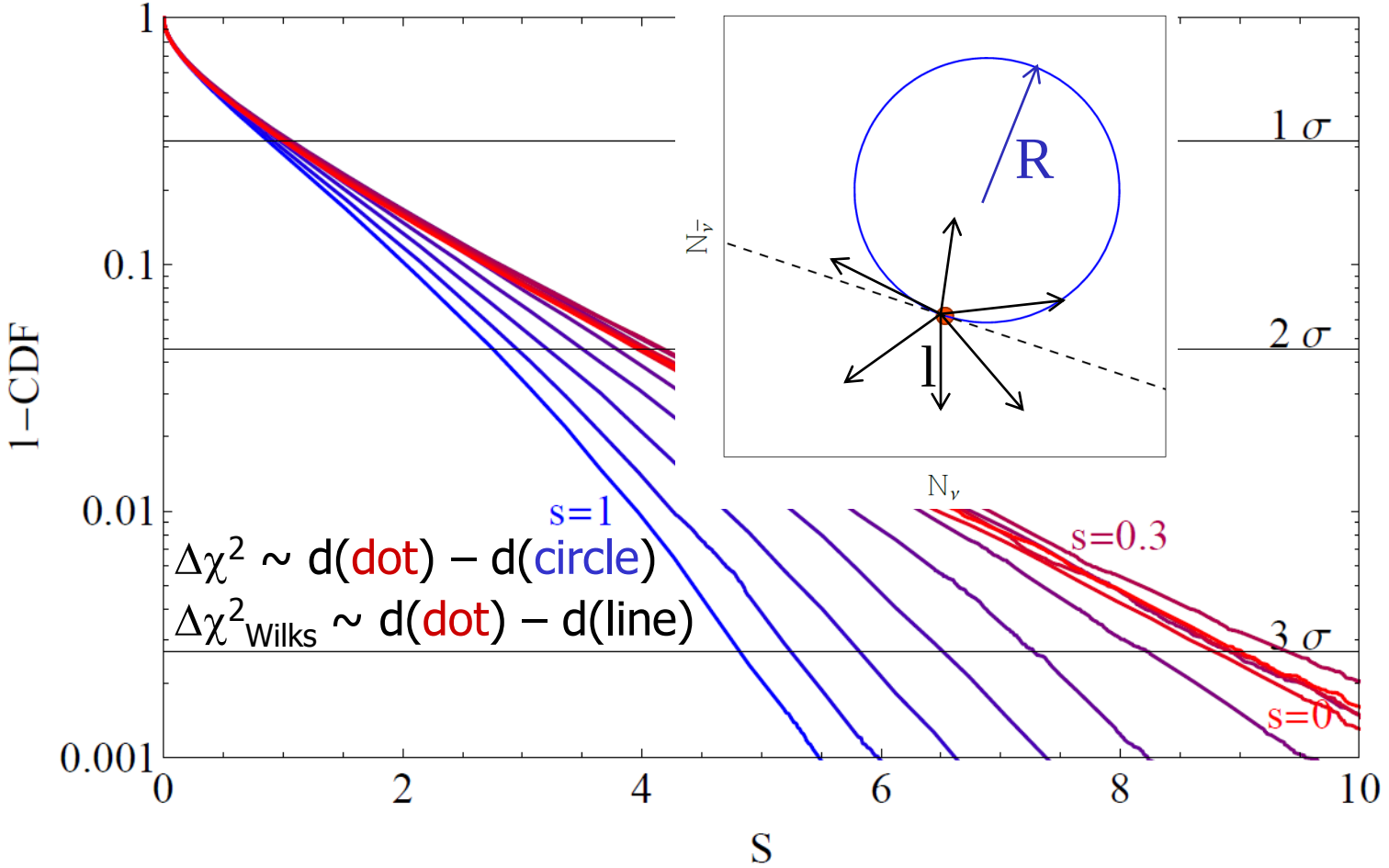

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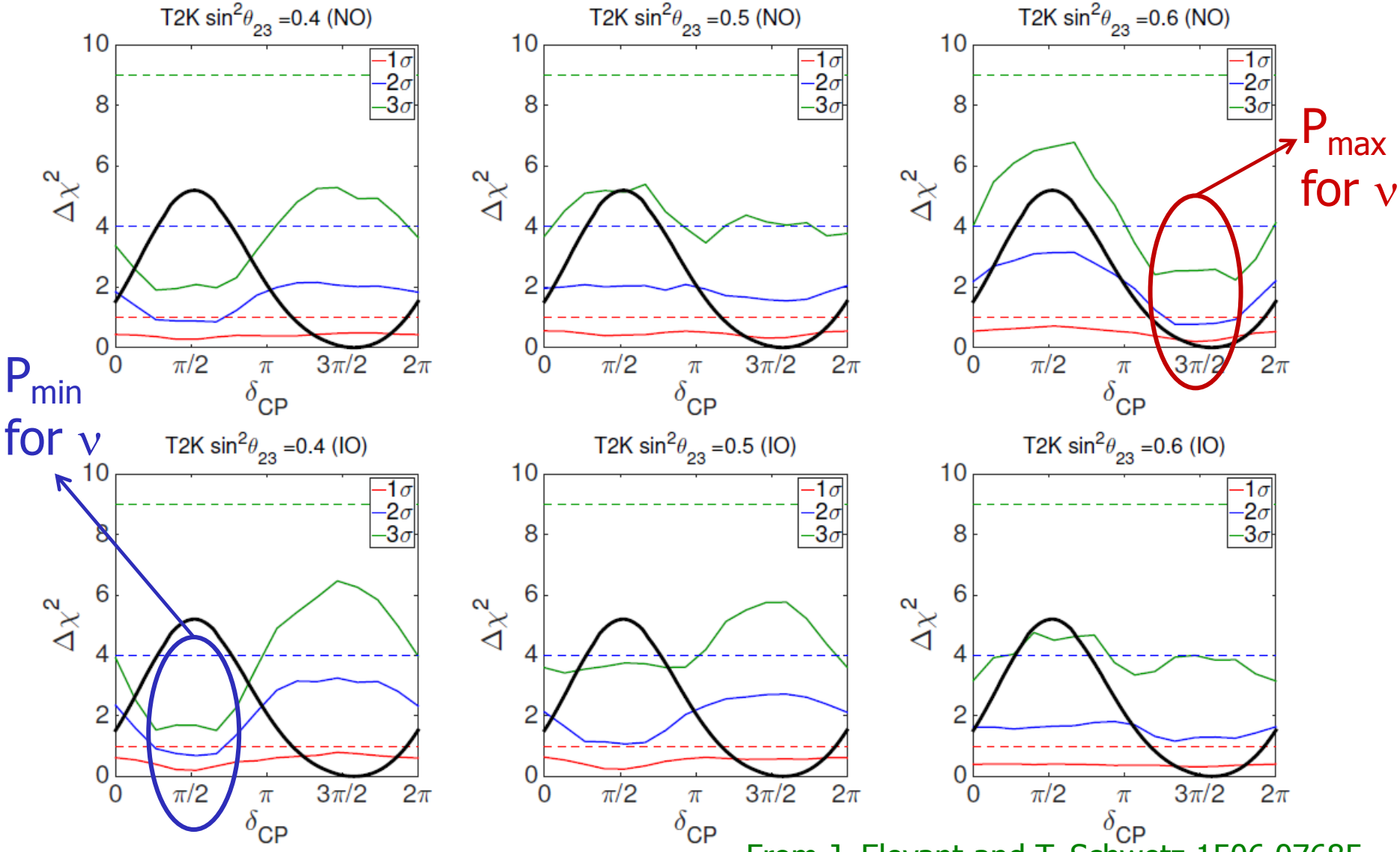
For s=0 χ^2 is recovered

M. Blennow, P. Coloma and EFM 1407.3274

Present hint? Significance??



From J. Elevant and T. Schwetz 1506.07685

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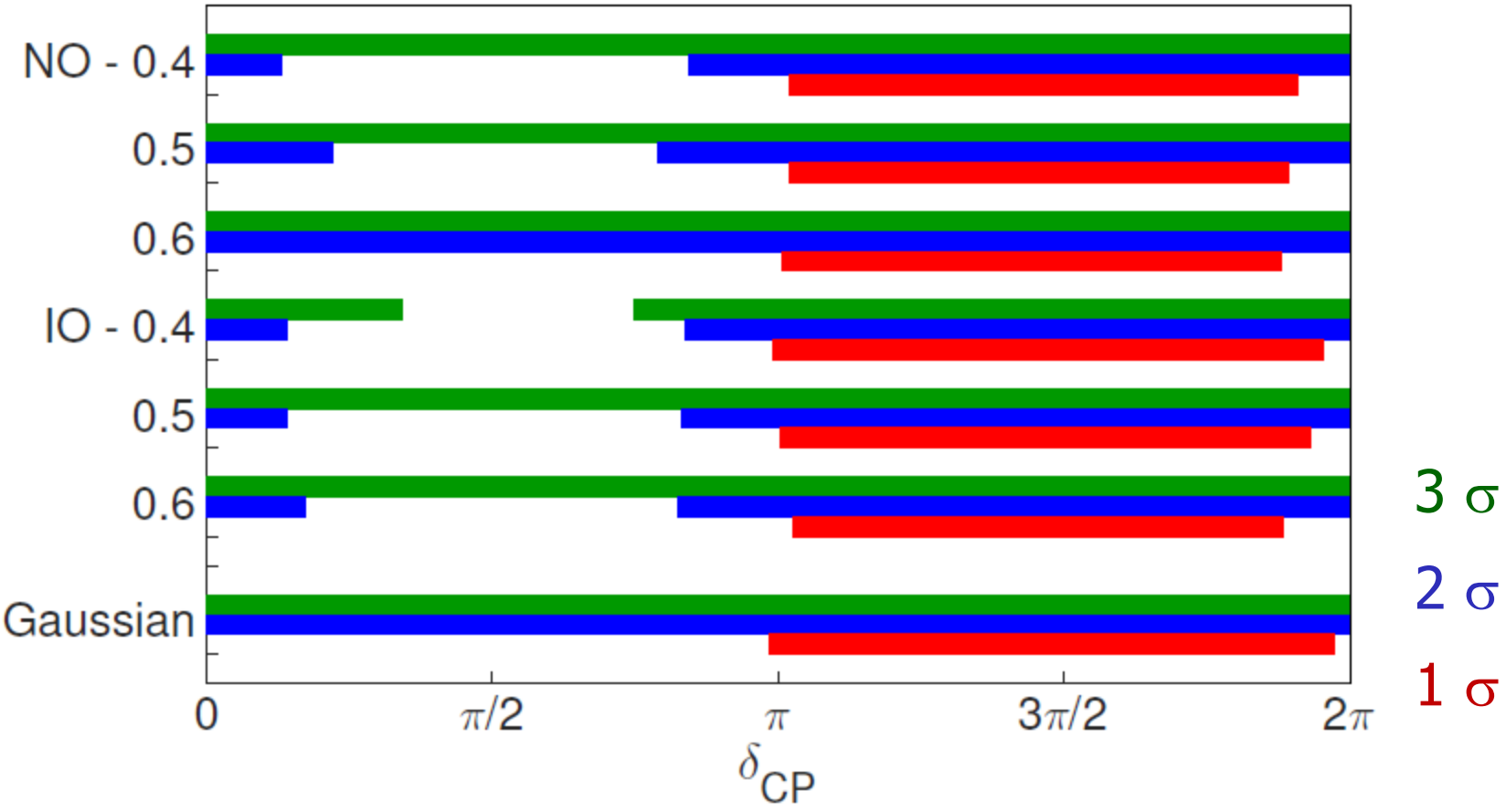

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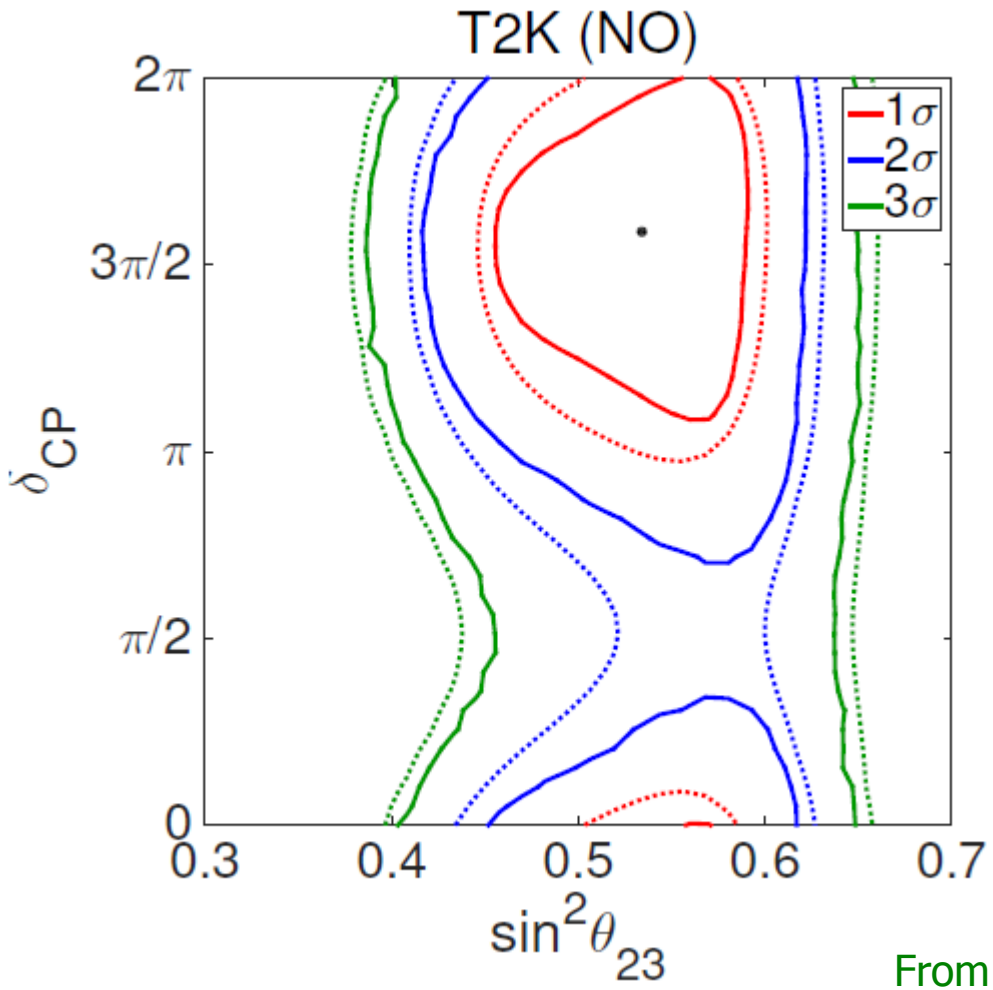


2D contour much closer to χ^2 approximation

From J. Elevant and T. Schwetz 1506.07685

Conclusions

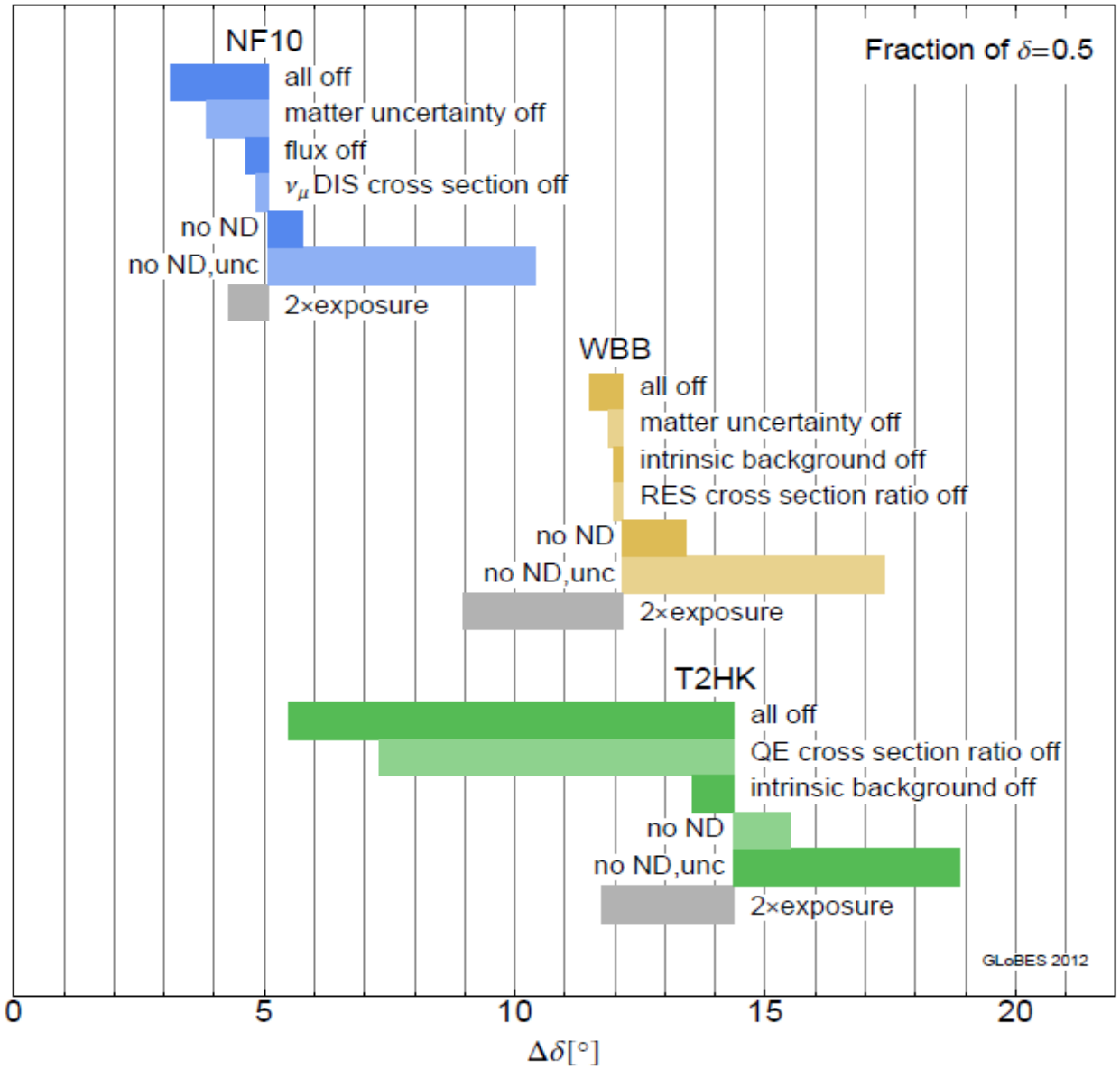
- The large value of θ_{13} discovered opens the window to the measurement of the neutrino mass hierarchy and leptonic CP violation.
- T2K and NOνA ~~will provide~~ are providing the first ~2-3 σ indications over the next years. In order to reach 5 σ discovery, upgraded or new facilities will be needed.
- The optimization strategy for CPV changes for large θ_{13}: importance of systematic errors and the second oscillation peak over statistics and backgrounds.
- Deviations from χ^2 in present facilities. Necessary to carefully calibrate the χ^2 when assessing present hint from T2K+Daya Bay+Noνa. Stay tunned!

Systematics

	SB			NF		
Systematics	Opt.	Def.	Cons.	Opt.	Def.	Cons.
Fiducial volume ND	0.2%	0.5%	1%	0.2%	0.5%	1%
Fiducial volume FD (incl. near-far extrap.)	1%	2.5%	5%	1%	2.5%	5%
Flux error signal ν	5%	7.5%	10%	0.1%	0.5%	1%
Flux error background ν	10%	15%	20%	correlated		
Flux error signal $\bar{\nu}$	10%	15%	20%	0.1%	0.5%	1%
Flux error background $\bar{\nu}$	20%	30%	40%	correlated		
Background uncertainty	5%	7.5%	10%	10%	15%	20%
Cross secs $\times$ eff. QE†	10%	15%	20%	10%	15%	20%
Cross secs $\times$ eff. RES†	10%	15%	20%	10%	15%	20%
Cross secs $\times$ eff. DIS†	5%	7.5%	10%	5%	7.5%	10%
Effec. ratio ν_e/ν_μ QE*	3.5%	11%	–	–	–	–
Effec. ratio ν_e/ν_μ RES*	2.7%	5.4%	–	–	–	–
Effec. ratio ν_e/ν_μ DIS*	2.5%	5.1%	–	–	–	–
Matter density	1%	2%	5%	1%	2%	5%

P. Coloma et al 1209.5973

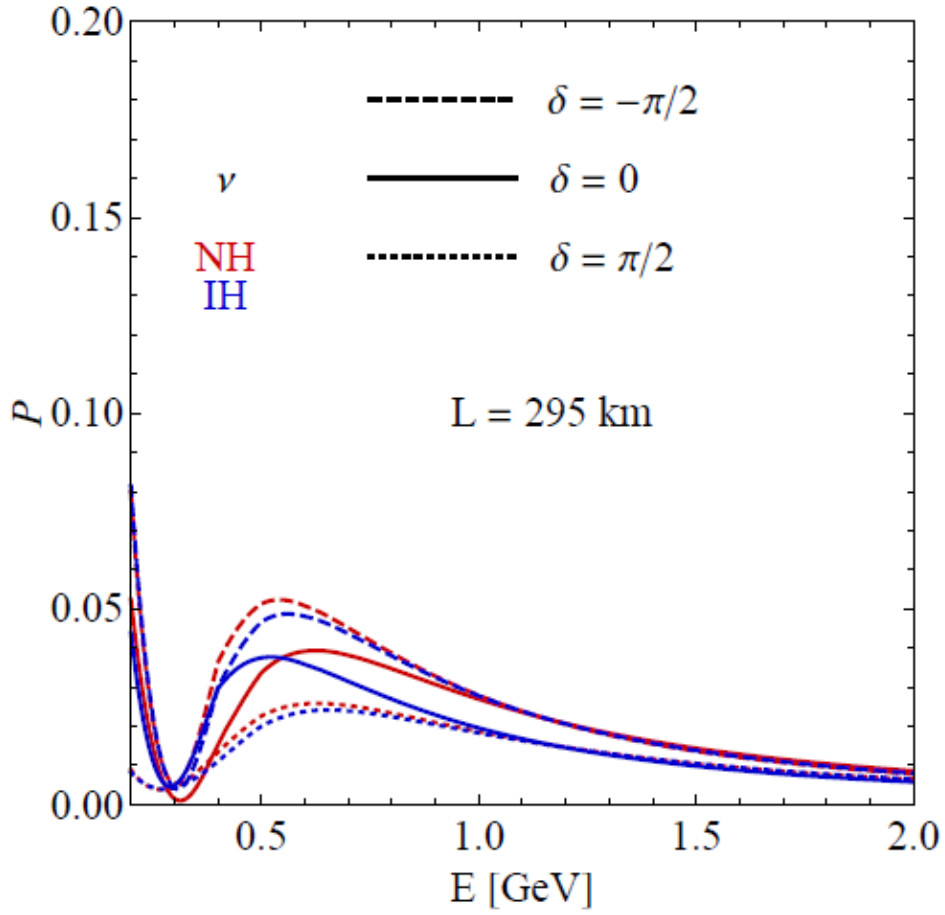
Systematics

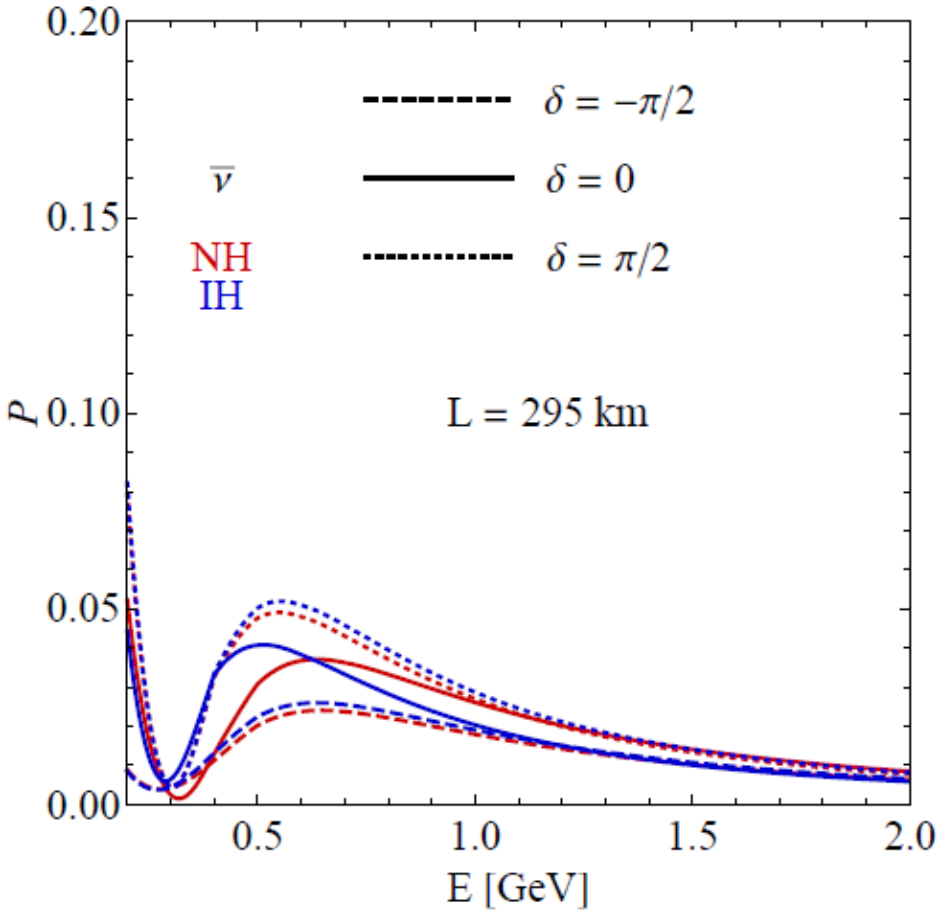


P. Coloma et al 1209.5973

Probabilities

T2K/T2HK

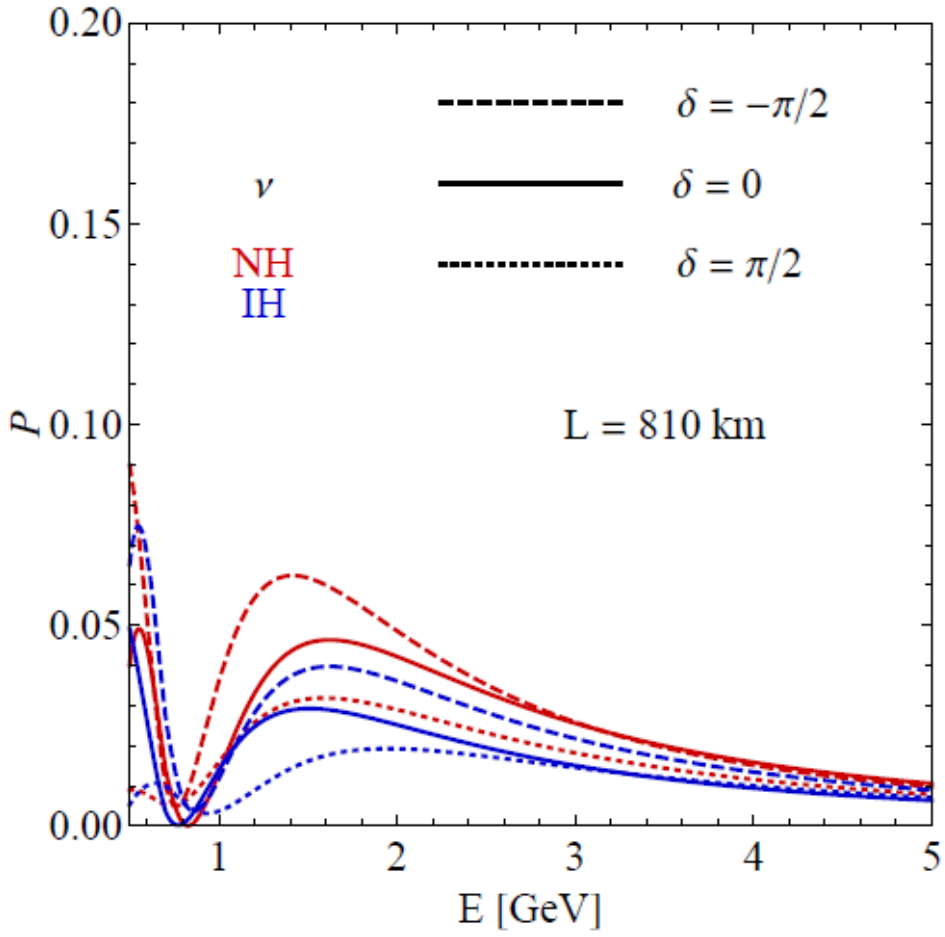


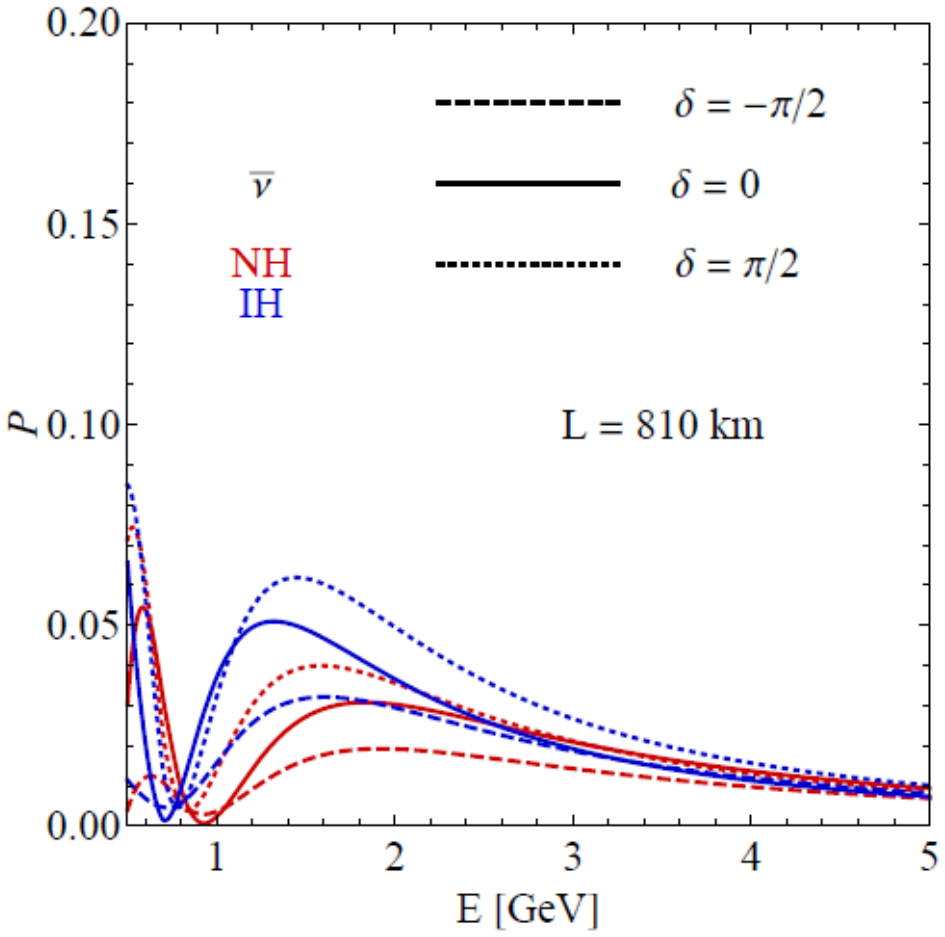


Plot from the Physics Briefing Book: Input for the Strategy Group to the European Strategy for Particle Physics

Probabilities

NOνA





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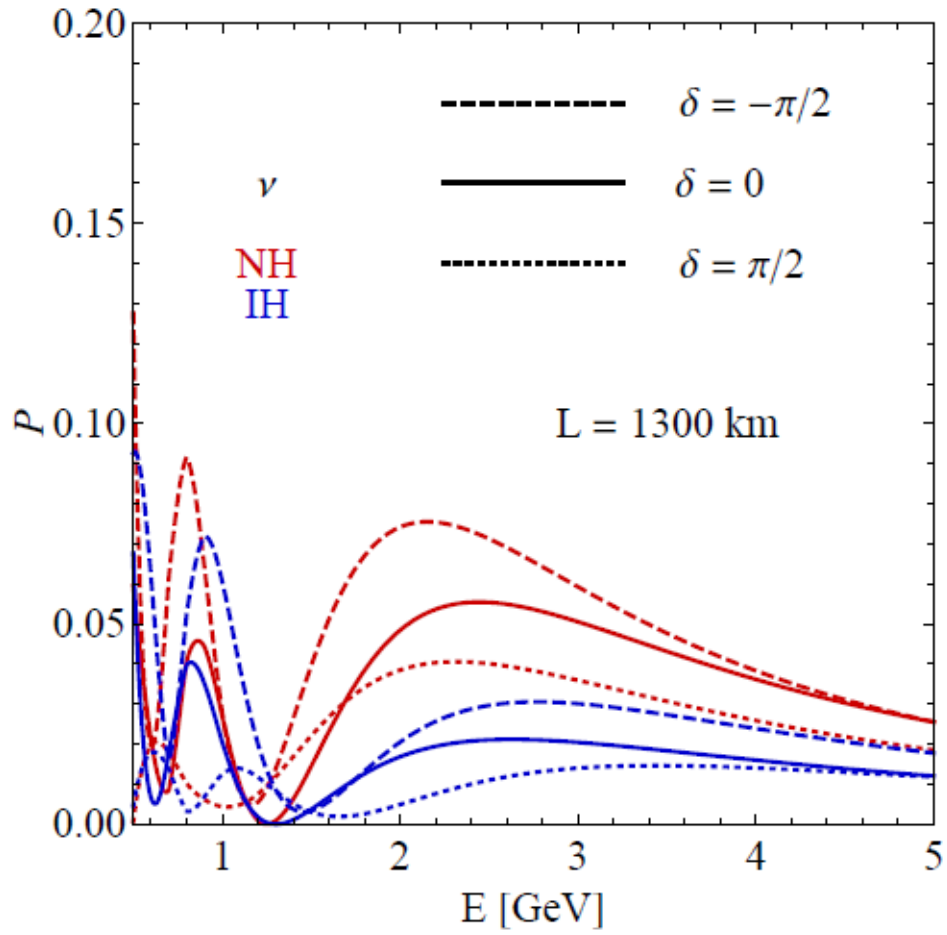
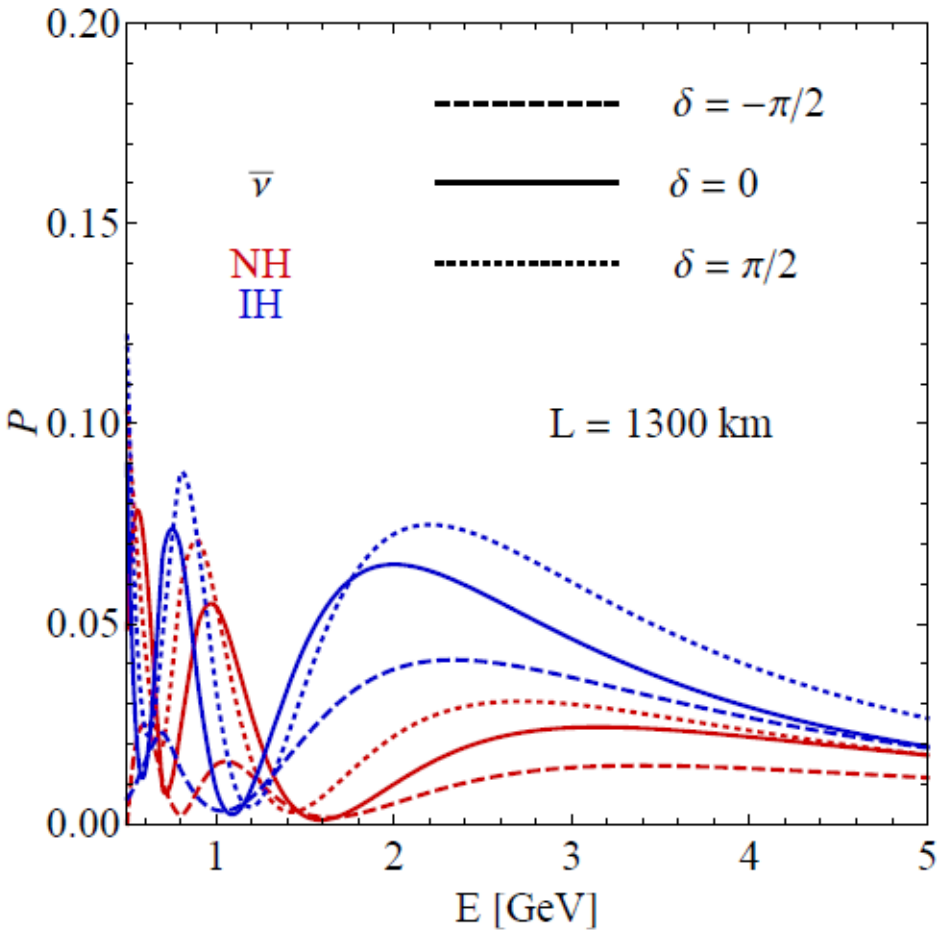
Probabilities

LBNE (LBNF)

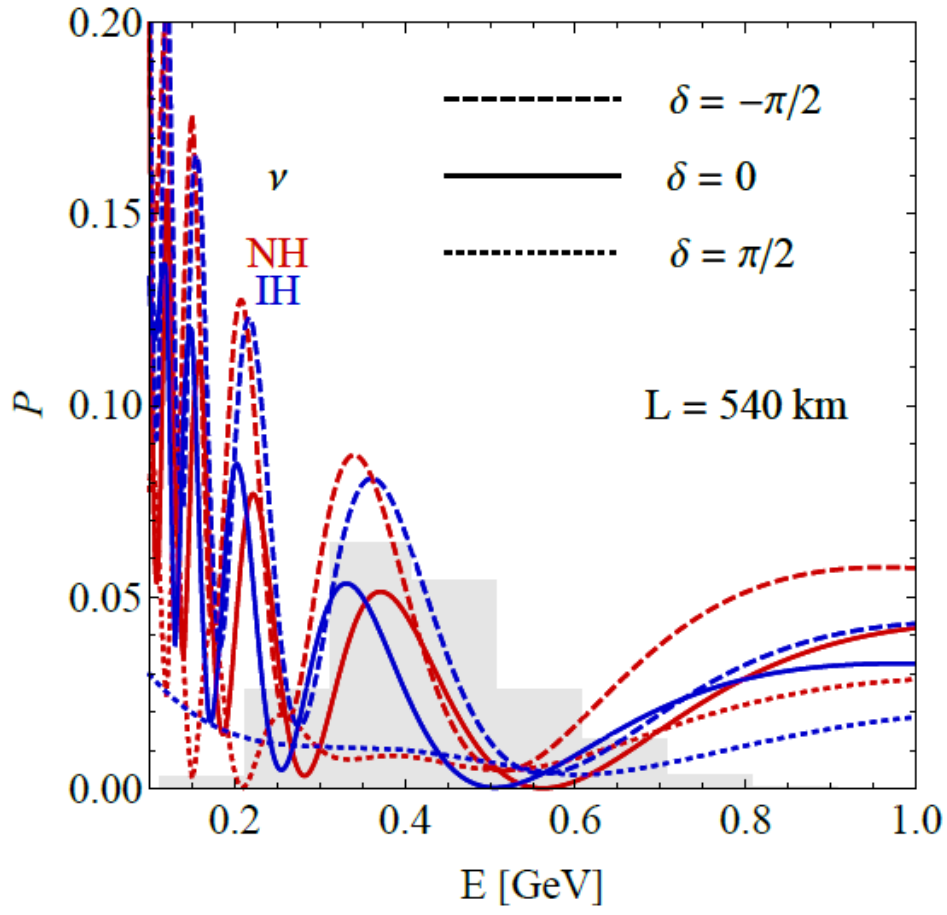


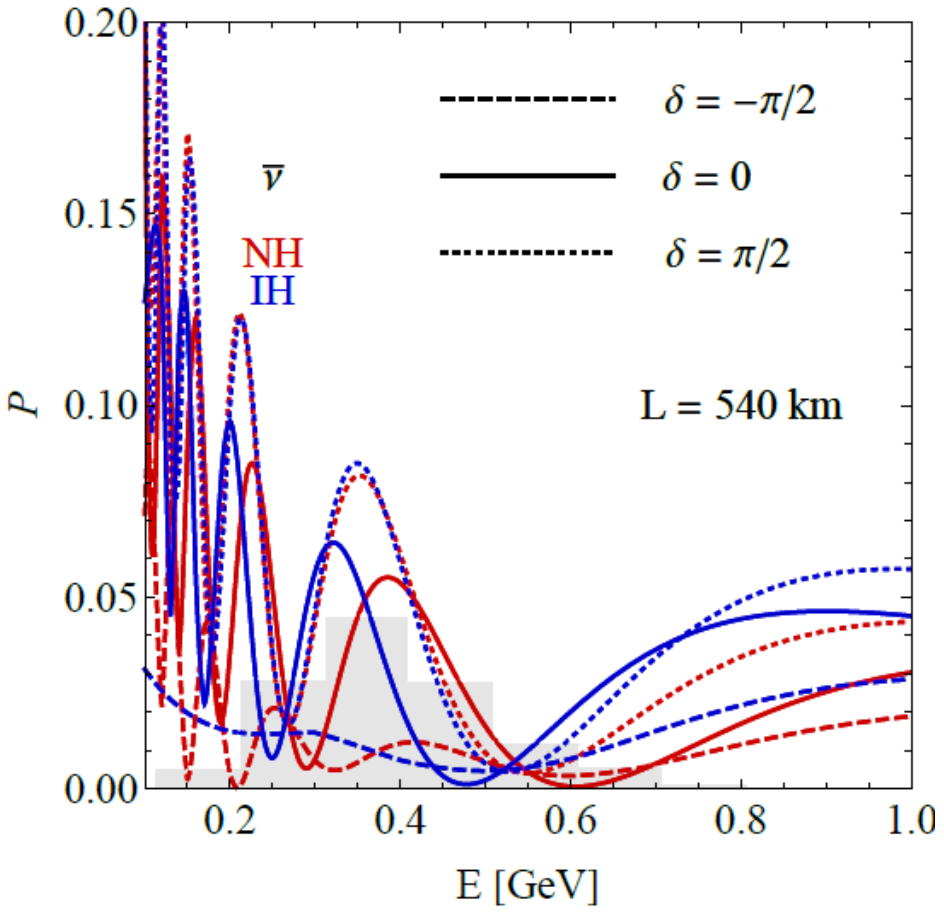


Plot from the Physics Briefing Book: Input for the Strategy Group to the European Strategy for Particle Physics

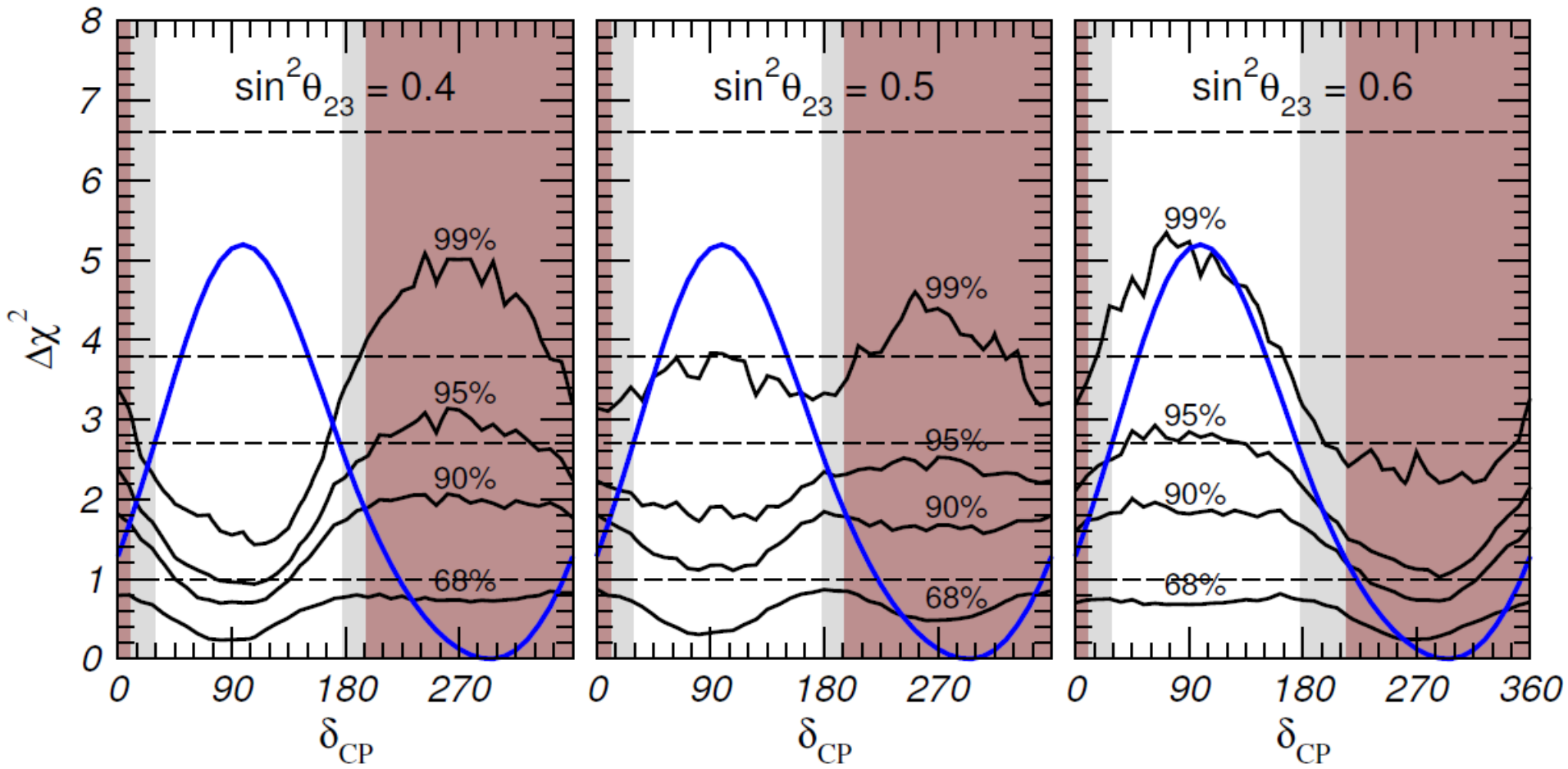
Probabilities

ESS





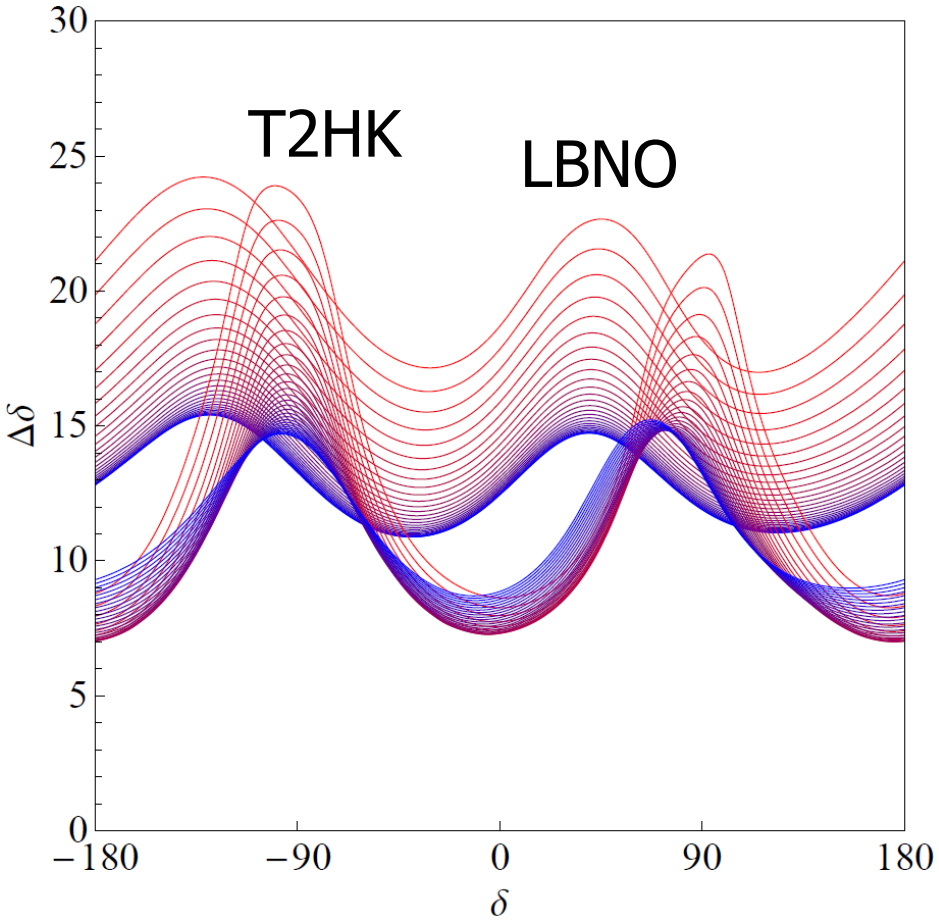
Present hint? Significance??

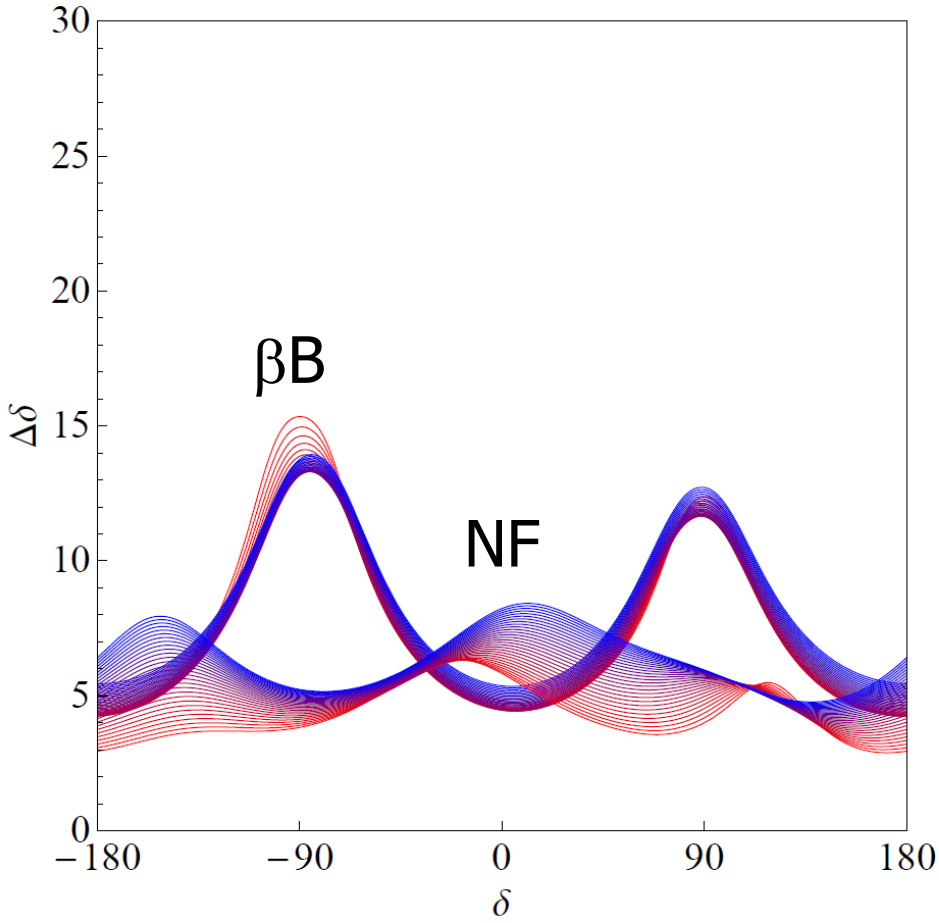


For the present hint for δ the effect is very strong and huge correlations with θ_{23} should be explored to assess significance!

From M. C. Gonzalez-Garcia, M. Maltoni, J. Salvado, T. Schwetz 1405.5439 www.nu-fit.org

Precision

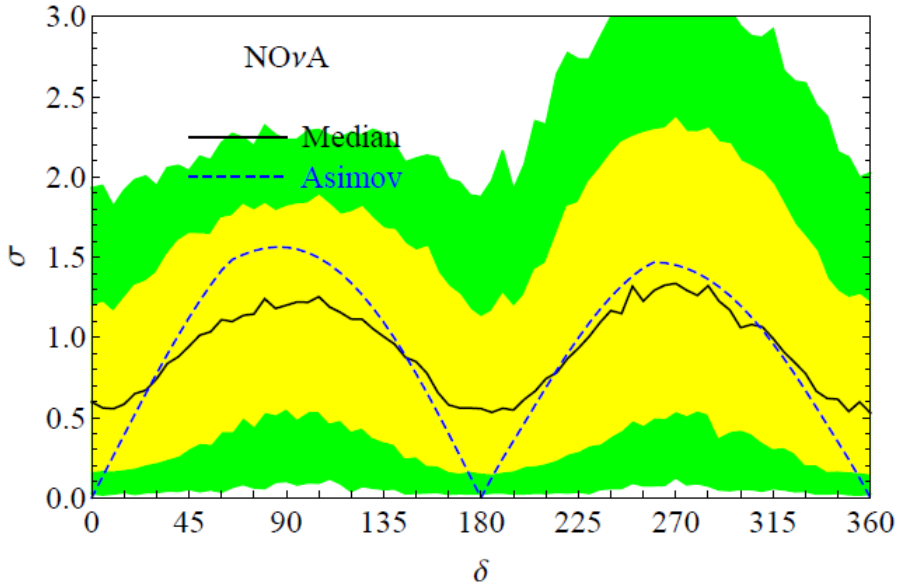


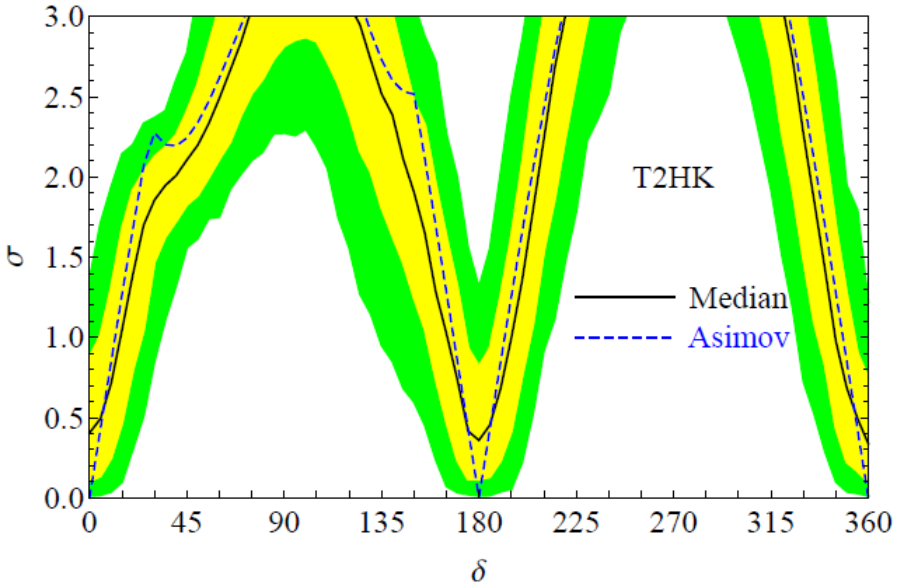


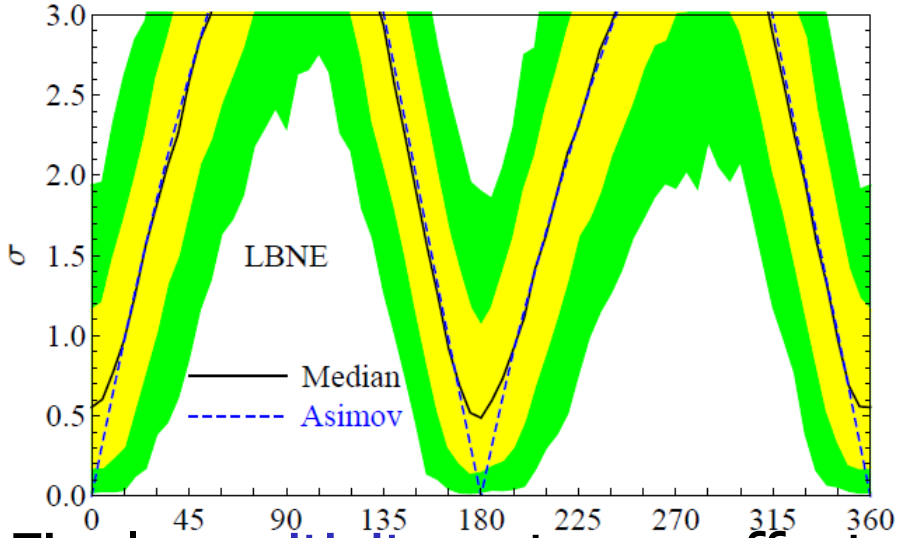
θ_{13}: 3º - 10º

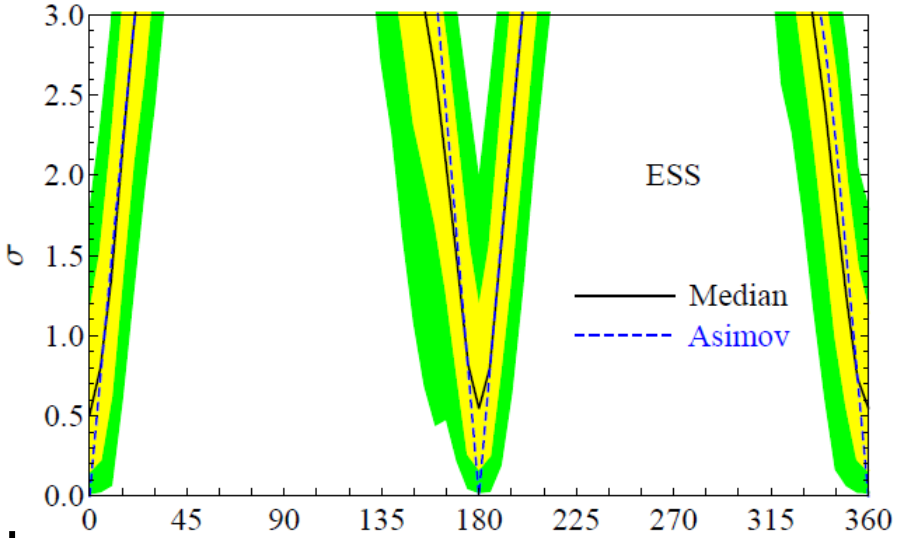
P. Coloma, A. Donini, EFM and P. Hernandez 1203.5651

Is it a χ^2?









Final sensitivity not very affected. M. Blennow, P. Coloma and EFM 1407.3274